# Crop response in the Western Cape of South Africa to liming soil under no-tillage and following once-off tillage in a no-tillage regime

by
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## ABSTRACT

Soil acidity, and the stratification thereof, was found throughout the Western Cape Province. Soil acidity is especially prevalent in the Swartland, where 19.3% of soils in this region have been found to contain at least one soil layer, in all cases deeper than 5 cm, with $pH_{(KCl)} \leq 5.0$. The mean acid saturation percentage of the Swartland region was above the 8% threshold for wheat production. The wide adoption of no-tillage has presented challenges to address subsoil acidity. Since soil acidity is a limiting factor for wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and canola (*Brassica napus*) grown in these regions, acidity should not remain unaddressed. Therefore, it is crucial that liming is done with the correct combination of liming material, method of application and physical incorporation, or lack thereof. These variables were evaluated on sandy loam soil with $pH_{(KCl)}$ 5.5. Results from this field trial indicate that micro-fine lime pellets and Class A calcitic lime yield similar results on soil chemical properties and crop response under the soil and climatic conditions that prevailed during this study. The in-row application of a small amount (40 kg $ha^{-1}$) of micro-fine lime pellets had a negligible effect on soil chemical properties and the treatment where only 40 kg $ha^{-1}$ of micro-fine lime pellets were applied was the only treatment, along with the control, where soil $pH_{(KCl)}$ decreased over the course of this trial. Comparison between samples taken in-row and between crop rows in the treatments where liming material was applied in-row and broadcast, showed a greater ($p \leq 0.05$) increase in Ca content in the samples taken between crop rows than in-row. Of the crop response variables measured, canola showed treatment responses ($p \leq 0.05$) in leaf area index (LAI), aboveground biomass and oil content. Canola LAI's only differed at 90 days after emergence (DAE), with the treatments where soil was disturbed and where micro-fine lime pellets were applied at 19% below the recommended rate having the highest LAI's. Where a disc plough was used and where micro-fine lime pellets were applied in-row only, oil contents were the lowest ($p \leq 0.05$). The crop responses in only some variables can be ascribed to the resilience of canola and the fact that lime application was done in the same year, thus the liming materials did not have sufficient time to react with soil acidity. In the following year, wheat was planted on the same site. This was done to monitor treatment effects over two years. Wheat showed treatment responses ($p \leq 0.05$) in plant population and aboveground biomass at 150 DAE. Where a disc plough was used, both the plant population and aboveground biomass was the highest. Increases in soil pH in the 5 – 15 cm soil depth layer positively correlated with

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increased aboveground biomass and wheat grain protein content. Increasing effective cation exchange capacity also correlated with increased aboveground biomass in wheat. The amount of rainfall, as well as rainfall distribution, may have contributed to the few treatment differences in 2020.

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## UITTREKSEL

Grondsuurheid, en die stratifikasie daarvan, is regdeur die Wes-Kaap Provinsie gevind. Grondsuurheid is veral algemeen in die Swartland, waar 19.3% van gronde in hierdie streek ten minste een grondlaag bevat, in alle gevalle dieper as 5 cm, met pH(KCl) ≤ 5.0. Die gemiddelde suurversadigingspersentasie van die Swartland streek was bo die 8% drempelwaarde vir koringproduksie. Die algemene aanneming van geenbewerking bied uitdagings met die aanspreek van ondergrondse suurheid. Aangesien grondsuurheid ‘n beperkende faktor is vir koring (Triticum aestivum), gars (Hordeum vulgare) en canola (Brassica napus) wat in hierdie streke verbou word, moet grondsuurheid aangespreek word. Dit is dus van kritieke belang dat bekalking met die korrekte kombinasie van kalkmateriaal, metode van kalktoediening en fisiese inkorporasie, of gebrek daarvan, gedoen word. Hierdie veranderlikes is geëvalueer op sanderige leemgrond met pH(KCl) 5.5. Resultate van hierdie veldproef dui daarop dat mikro-fyn verkorrelde kalk en Klas A kalsitiese kalk soortgelyke effekte op grond chemiese eienskappe en gewasreaksie tot gevolg het onder die grond-en klimaatstoestande wat tydens hierdie studie geheers het. Die toediening van ŉ klein hoeveelheid (40 kg ha-1) mikro-fyn verkorrelde kalk binne die ry het ŉ weglaatbare effek op grond chemiese eienskappe gehad en die behandeling waar slegs 40 kg ha-1 van die mikro-fyn verkorrelde kalk toegedien is, was die enigste behandeling, buiten die kontrole, waar die pH(KCl) van die grond afgeneem het deur die verloop van hierdie studie. Vergelyking van monsters wat binne die rye en tussen rye geneem is van die behandelinge waar kalkmateriaal binne rye en breedwerpig toegedien is, het ŉ groter ($p \leq 0.05$) verhoging in die kalsiuminhoud getoon van die monsters wat tussen die rye geneem is. Van die veranderlikes wat gewasreaksie gemeet het, het canola behandelingsreaksies ($p \leq 0.05$) in blaaroppervlakindeks (BOI), bogrondse biomassa en olie-inhoud getoon. Die BOI van canola het slegs by 90 dae na opkoms (DNO) verskil, waar die behandelinge waar grond versteur was en waar mikro-fyn verkorrelde kalk teen 19% minder as die aanbeveelde toedieningspeil toegedien is, die hoogste BOI getoon het. Waar ŉ skottelploeg gebruik was en waar mikro-fyn verkorrelde kalk slegs in die rye toegedien was, was olie-inhoud die laagste ($p \leq 0.05$). Gewasreaksie in slegs sommige veranderlikes kan toegeskryf word aan canola se veerkragtigheid en aan die feit dat die bekalking in dieselfde jaar gedoen is, dus het die bekalkingsmateriaal nie voldoende tyd gehad om volledig te reageer met grondsuurheid nie. In die volgende jaar is koring op dieselfde proefperseel geplant. Dit was gedoen om die behandelingseffekte oor twee jaar te monitor.

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Koring het behandelingseffekte ($p \leq 0.05$) in plantpopulasie en bogrondse biomassa by 150 DNO getoon. Waar 'n skottelploeg gebruik was, was beide plantpopulasie en bogrondse biomassa die hoogste. Verhogings in grond-pH in die 5 – 15 cm diepte het positief gekorreleer met verhoogde bogrondse biomassa- en proteïeninhoud van koring. Verhoging in die effektiewe katioon-uitruilvermoë het ook gekorreleer met verhoogde bogrondse biomassa van koring. The hoeveelheid reënval, sowel as die reënvalverspreiding, mag bygedra het tot die min verskille tussen behandelings in 2020.

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# Chapter 1: Introduction

## 1.1 Background

Soil acidity is a problem that is widespread and is often present in agricultural production systems throughout the world (Arshad *et al*., 2012). Soil acidification is a process that occurs naturally, however certain farming practices, such as usage of ammonium-based fertilisers, may aggravate soil acidification due to the release of $H^+$ from the $NH_4^+$ group (Robbins and Voss, 1989). Acid soils are ameliorated through the application of either calcitic limestone ($CaCO_3$) or dolomitic limestone ($CaMg(CO_3)_2$), which raises the pH of soil (Caires *et al*., 2006). It is widely accepted that the neutralising effect of limestone application is limited to the area of application as limestone is not very soluble and only mobile in acid soils (Farina *et al*., 2000). Due to immobility, mixing limestone into soil through tillage is most efficient in ameliorating soil acidity in the entire profile (Auler *et al.*, 2017; Fageria and Baligar, 2008). The tillage action required for the incorporation of limestone into the soil does however have detrimental effects on the soil, such as degrading the soil structure and decreasing the organic matter content of the soil (Arshad *et al*., 1999). The advantages of no-tillage surpass the disadvantages and is preferred among producers in many areas (Giarola *et al*., 2013; Llewellyn *et al*., 2012; Triplett and Dick, 2008). When limestone is applied in no-tillage systems, it has to be broadcasted on the soil surface and is not mechanically incorporated into the soil. Surface application of limestone only allows for the top few centimetres of the soil profile to react with the limestone (Caires *et al*., 2008; Ernani *et al*., 2004). Therefore, long-term no-tillage practices may lead to large pH contrasts between the topsoil and deeper soil layers, potentially with alkaline topsoil and acid soil in deeper layers. Nutrient stratification may also occur in no-tillage soil, particularly immobile nutrients such as P, and availability of nutrients to plants may be affected by stratification of pH between the various depth layers within the soil.

The stratification of soil acidity is often not picked up when soil samples are taken. Soil samples are usually only taken to a 15 cm depth and the soil analysis then effectively gives an average for the various chemical attributes such as pH and exchangeable acidity over the 15 cm depth. This implies that the soil analyses do not depict the stratification of the top and sub-soil layers due to the dilution effect of that results from the sampling method. Stratification of pH in soil is a serious growth-limiting factor for crop production, due to the availability of nutrients to

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crops being influenced by pH, as well as the roots of crops potentially being damaged by Al toxicity at depths with a low pH (Caires *et al*., 2008).

**1.2 Problem statement**

Barley (*Hordeum vulgare*), wheat (*Triticum aestivum*) and canola (*Brassica napus*) are three economically important crops throughout the Western Cape Province of South Africa, as well as other regions across the globe that have a Mediterranean-type climate (del Pozo *et al*., 2019).

In South Africa, 89% of barley is produced in the Western Cape under dryland agriculture (DAFF, 2017). Canola and barley both have an optimal $pH_{(KCl)}$ of 5.5 and is therefore sensitive to soil acidity where the $pH_{(KCl)}$ of the soil is below 5.5. Both barley and canola have deep root systems with root growth often only being limited by the depth of the soil profile, however, a soil $pH_{(KCl)}$ less than 5.5 will inhibit further root growth and development and thus the development of the plant as a whole. This is largely because of an increase in Al bioavailability as the soil pH decreases, which causes Al phytotoxicity and nutrient deficiencies, as Al competes with the uptake of other nutrients (Caires *et al*., 2008).

No-tillage has been found to lead to nutrient stratification over soil depth (Scheiner and Lavado, 1998). The stratification of soil pH was also observed, along with the stratification of soil nutrients (Crozier *et al*., 1999). This is relevant to farmers in the Western Cape, as more than 60% of farmers follow conservation agriculture fully and more than 90% of farmers have converted to no-tillage system and are therefore potentially prone to subsoil acidity in the long term (Findlater *et al.*, 2019).

To approach this problem, a few possible solutions can be considered. Previous research on wheat, canola and annual *Medicago* spp. (mostly *M. trancatula* and *M. polymorpha*) has shown that a once off strategic tillage has no effect on plant production and soil quality and can thus be a suitable way of incorporating limestone into the subsoil to reduce subsoil acidity (Dang *et al.*, 2015; Liu *et al.*, 2016). In such cases, a fine limestone could be considered as a potential solution, as this may possibly move more efficiently to the deeper soil layers than a coarser limestone. This fine limestone would have to be pelletised or granulated, as applying it with conventional lime spreaders would not allow for efficient application. Pelletised or

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granulated limestone can be applied on the soil surface over which the seed-drill will move during the planting process. This action will automatically integrate some of the limestone to the depth of the seed-drill operation (usually about 5 to 10 cm). Alternatively, limestone pellets or granules could be mixed with fertilisers and band placed in the seed furrow, thus placing the limestone more efficiently at depths of 5 to 10 cm.

The pelletisation of limestone may however not be a workable solution. The pelletisation process may be economically unviable and advantages over standard class A lime could not warrant the extra cost associated with this product when the potential yield increases are weighed against the production cost of pelletised limestone products. Pelletised limestone products may also differ in solubility, depending on the cementing agent used. This could potentially cause the application of the pelletised limestone to not have the desired neutralisation effect, if the cementing agent that surrounds the limestone does not dissolve easily. This may lead to the presence of undissolved pellets in the soil and therefore the acidity in the soil may potentially remain unaddressed after the application of the pelletised product.

### 1.3 Aim and objectives

The aim of this study was to determine the most effective liming strategies for crop rotation systems in the Western Cape Province of South Africa.

This study had the following objectives:

1. to conduct a survey to determine the geographical spread and severity of pH stratification in long term no-tillage soils across the Western Cape Province.
2. to determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on soil chemical attributes.
3. to determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on the growth and development of canola and wheat.

### 1.4 Outline of thesis

This thesis consists of five chapters, which includes this introductory chapter. This chapter contains background information regarding soil acidity and the various methods of liming soil

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to address acidity problems in different tillage management systems, as well as the aim and objectives of the study.

Chapter two is a literature review covering soil acidity, the different methods of acidity amelioration, the most widely used products to ameliorate soil acidity as well as the effect of acidity and liming on various crops that are economically important to the Western Cape of South Africa.

Chapter three covers a soil survey that was conducted in order to investigate the severity and geographical spread of soil acidity throughout the southern Cape and Swartland regions of the Western Cape of South Africa. This chapter was published in a peer-reviewed journal with an Impact Factor (2019) of 2.429 and is attached in the published format as Addendum A. The article can be cited as: Liebenberg, A., Van Der Nest, J.R.R., Hardie, A.G., Labuschagne, J. and Swanepoel, P.A., 2020. Extent of soil acidity in no-tillage systems in the Western Cape Province of South Africa. Land, 9(10), p.361. The author of this thesis declares a significant contribution to the published article, including the following: Methodology, Formal analysis, Investigation, Data curation, Writing—original draft preparation, and Validation.

Chapter four covers a field trial that was conducted near Caledon in the Western Cape in order to investigate the effects of various forms of physical disturbance as well as various forms, purities and fineness of limestone on canola and wheat crops.

Chapter five is the conclusions and recommendations that were drawn from the content of this study.

Three appendices are attached to this thesis:

- Appendix A is the reference to the published version of the soil survey of Chapter 3.
- Appendix B is the questionnaire the producers completed to obtain information regarding the field and crop history, as well as their lime application and management.
- Appendix C contains the initial soil sample analyses of the trial site used for Chapter 4.

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# Chapter 2: Literature Review

## 2.1 Causes of soil acidity

Soil pH, either too low or too high, can be a limitation to crop production (Fernández and Hoeft, 2009). The lower end of the pH scale is associated with acid conditions and indicates high concentrations of $H^+$ and $Al^{3+}$ in the soil solution. Soil acidity is a widespread problem throughout the world, and it is found in all types of production systems (Arshad *et al*., 2012). Roughly 30% of topsoils worldwide are affected by acidity and furthermore 75% of soils that have an acidic topsoil, are also affected by subsoil acidity (Sumner and Noble, 2003). Acidification of soils does occur naturally, however the natural rate of soil acidification can be accelerated by certain farming practices. Natural acidification can be ascribed to parent material being acidic, parent material having low concentrations of basic cations, such as $Ca^{2+}$ and $Mg^{2+}$, or due to high amounts of rainfall that causes the leaching of basic cations out of the soil profile (Fageria and Baligar, 2008). Rain may also contribute to soil acidity and is referred to as acid rain, which may contain dissolved acids such as carbonic acid (Goulding, 2016). Acidification of soil is a very slow process. For instance, 24 years after a once off liming done on a natural grassland in Brazil, only 20% of the original acidity measured was present (Rheinheimer *et al*., 2018). Some of the farming practices that contribute to acidification include the incorrect usage of ammonium-based fertilisers, the removal of basic cations as part of harvested crops, the leaching of basic cations due to over-irrigation and the build-up and successive decomposition of organic matter that increases the concentration of organic acids (Barak *et al*., 1997; Crusciol *et al*., 2011; Goulding, 2016; Robbins and Voss, 1989). Nitrification of ammonium-based fertilizers, through the action of *Nitrosomonas* and *Nitrobacter* in soils, generates $H^+$ ions as illustrated by Equations 1-3, and this is the primary reason for a decline in pH in cropped soils receiving high rates of N fertilizer.

Ammonium nitrate: $NH_4NO_3 + 2\text{º}_2 \rightarrow 2HNO_3 + H_2O$ (1)

Urea: $CO(NH_2)_2 + 4O_2 \rightarrow 2HNO_3 + H_2O + CO_2$ (2)

Ammonium sulphate: $(NH4)_2SO_4 + 4O_2 \rightarrow 2HNO_3 + H_2SO_4 + 2H_2O$ (3)

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In the case of ammonium sulphate, additional acidity in the form of sulphuric acid is produced. This accounts for the fact that, per unit of N applied, ammonium sulphate has a far greater acidifying potential than ammonium nitrate or urea.

The continuous use of legumes in a cropping system also contributes to soil acidity over time (Fageria and Baligar, 2008). This is due to the high amounts of N that is added to the soil by the legumes, which forms $NH_4^+$ as an end product of the decomposition of the roots of leguminous crops (Goulding, 2016). This decrease in soil pH can further be attributed to the increase in organic matter in these soils that are the result of no-tillage, which is a widely adopted management strategy in the Western Cape of South Africa, as well as multiple countries worldwide (Bayer *et al*., 2000; Brown *et al*., 2008; Rhoton, 2010). Organic matter does however contain some basic cations that remain in residues after the crop had been harvested, as well as improving the buffer capacity of the soil, which assists to restrict the content of exchangeable acidity in the soil solution (Liu and Hue, 2001; McCauley *et al*., 2009). The residues that remain on top of the soil after harvest also has other benefits, such as the retention of soil water and protecting the soil against wind and water erosion (Klocke *et al*., 2009; Fryrear, 1985).

The build-up of organic matter does however increase the concentrations of organic acids in soil under no-tillage, further contributing to soil acidity (Ritchie and Dolling, 1985; Goulding, 2016). This is due to the decomposition of the organic matter that releases organic acids. Decomposition of plant residues that remain on top of the soil after harvesting will release organic acids with low molecular weights, which can bind basic cations, such as $Ca^{2+}$ and $Mg^{2+}$, and transport them deeper into the soil profile (Rheinheimer *et al*., 2018). This downward movement of basic cations deeper into soil may help to alleviate the effects of subsoil acidity if the corresponding alkalinity component ($OH^-/HCO_3^-$) also moves into the soil profile.

The aforementioned process of basic cation movement into soils may however not be applicable to the movement of limestone itself deeper into soil. Caires *et al*. (2008) found that organic soil cover in the form of black oats (*Avena strigosa*) residues did not improve the mobility of surface applied limestone to address acidity problems in the subsoil. The decomposition of organic matter also releases basic cations that were part of the crop residues, which may help to raise soil pH. The majority of organic materials however do not

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contain adequate concentration of basic cations, such as Ca, to raise the concentration thereof in deficient soils (Hue and Liu, 2001). That being said, this process could contribute to maintaining a high level of basic cations over time in soils that are not deficient.

It has been stated that soil amendments that contain $Mg^{2+}$ or $Ca^{2+}$ (such as calcitic- and dolomitic limestones) can be associated with increased aggregate stability, due to the bonding of soil particles that involve $Ca^{2+}$ bridges (Chan and Heenan, 1999). Aggregate stability influences various processes involving both plants and soils. Some of the processes that are influenced by aggregate stability include root elongation and root density, the formation of macropores in soil as well as the overall macroporosity of the soil, soil water holding capacity, soil aeration, water infiltration rate and runoff, as well as influencing the rate of water and wind erosion (Amezketa, 1999; Zhao *et al*., 2017).

### 2.2 Compounds that Ameliorate soil acidity

This section mainly focuses on the use of limestone. However, some other compounds will be discussed in short due to the availability of compounds other than limestone to ameliorate acidic soils. Though they will be discussed briefly, these other compounds are outside the scope of this study.

#### 2.2.1 Limestone

Although the ideal soil pH range is crop specific, the challenge of acid soils can be addressed through the application of limestone (Caires *et al*., 2006). Calcitic or dolomitic limestones may be applied, depending on the concentration of $Mg^{2+}$ in the soil. The reaction of limestone with soil acidity may be depicted by Equations 5 and 6.

$$\text{Colloid-}(H^+)_2 + CaCO_3 \rightarrow \text{Colloid-}(Ca^{2+}) + H_2O + CO_2 \quad (4)$$

$$\text{Colloid-}(Al^{3+})_2 + 3\ CaCO_3 + 3\ H_2O \rightarrow \text{Colloid-}(Ca^{2+})_3 + 2\ Al(OH)_3 + 3\ CO_2 \quad (5)$$

The liming of acid soil increases soil pH, raising the concentrations of P and Mo and the availability of exchangeable $Mg^{2+}$ and $Ca^{2+}$. It also improves the retention of basic cations through the increase of negative charges on the edges of soil colloids by dissociating $H^+$-atoms from the hydroxyl ($OH^-$) groups on the edges of soil colloids (Sumner, 1995, Caires *et al*., 2005, Caires *et al*., 2006; Fageria and Baligar, 2008). The increased concentrations of P and Mo are

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due to these nutrients becoming more soluble and more plant available due to the raised pH that is the result of liming. The $H^+$-atoms that dissociate from the colloids bind to the carbonate group of the limestone to form carbonic acid ($H_2CO_3$). The $H_2CO_3$ freely dissociates to form water and carbon dioxide ($CO_2$). That being said, adding limestone to soils that are not acidic will not allow for the limestone to react, since there are no $H^+$ ions bonded to the hydroxyl groups on the soil colloids, which are required for the exchange reaction with the $Ca^{2+}$ ions from the liming material. Limestone does however have a low solubility along with a low mobility in soil, therefore the neutralisation reaction due to liming tends to occur only in the layer where it is applied (Caires *et al*., 2006). Even though it is known that liming chemically ameliorates subsoil acidity, the efficacy of the liming action is influenced by environmental factors, such as rainfall, and the quality of the limestone that is used (Farina *et al*., 2000). The efficacy of the liming action being dependant on the limestone quality is supported by various sources that found that finer limestone is more effective than coarser limestone to ameliorate acidity in soils (Haby and Leonard, 2002; Fageria and Baligar, 2008). It could then mean that application of the same amount of limestone may differ substantially in the rate of neutralising soil acidity when applied at different locations, depending on the limestone used and the various environmental factors of that specific location.

Liming also reduces the amounts of both the exchangeable $Al^{3+}$ and $Al^{3+}$-saturation of soils (Auler *et al*., 2017; Caires *et al*., 2006). Adequate liming also contributes to the prevention of both Mn and $H^+$ toxicities (Fageria and Baligar, 2008). Both of these statements can be attributed to the soil pH being raised as a result of liming and the subsequent effect thereof on the availability of nutrients. Increases in soil pH and exchangeable Ca has been correlated with a decrease in exchangeable Al, however the increase in exchangeable Ca was greater than the decrease in exchangeable Al (Whitten *et al*., 2000). It was also found that liming improved the availability of Ca, Mg, P and K after 12 months of limestone application, even though no difference in soil pH was observed in this same time period (Crusciol *et al.,* 2016). This improved availability of macro nutrients was observed as deep as 0.6 m after 24 months following the application of limestone. The composition of the parent material of this soil, as well as the rainfall received could have influenced these changes. The higher pH that is a result of liming had also been found to raise the adsorption affinity of iron oxides and organic material, along with other adsorptive surfaces (Suave *et al*., 2000). It is stated that for subsoil

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acidity to be influenced by liming, the basic anions (either $HCO_3^-$ or $OH^-$) need to move deeper into the soil by means of mass flow (Sumner, 1995). For this movement by mass flow to take place, water is required as a medium to move these anions into the subsoil.

Limestone is generally either applied as a surface application, which is more prevalent in no-tillage systems, or it is applied and physically incorporated into the soil. It has been proposed that in cases where tillage incorporation of limestone wants to be avoided, two options are available. Firstly, that the rate of limestone applied should be higher than the recommendation, to increase the rate of movement of limestone through the soil, as well as to increase the final depth reached by limestone (Conyers *et al.,* 2003). Secondly, the other option is to routinely analyse the soil to apply limestone before the amount of exchangeable Al in the soil increases substantially (Conyers *et al*., 2003).

Even though limestone is the most widely used material to ameliorate soil acidity, various different types of materials are used for this purpose, with varying levels of success. Crusciol et al. (2016) evaluated several of these materials. The increase in base saturation observed for all treatments is due to increased concentrations of $Ca^{2+}$ and $Mg^{2+}$ in the soil (Crusciol et al., 2016). This increase could be due to the liming materials directly adding $Ca^{2+}$ to the soil, or it could be due to the raised pH of the soil as a result of liming which improves the availability of $Ca^{2+}$ and $Mg^{2+}$ already present in the soil.

In recent years, micronised and/or finely ground particles of limestone have been pelletised by the addition of a water-soluble cementing agent. The structural integrity of these pellets ensures that this product can pass through the various types of seed-drills that are available, unlike the powdered limestone that needs to be applied by means of a lime spreader. This is however an expensive product and can only be applied in smaller amounts than the powdered limestone and tends to be only used as a method of maintenance (Higgins *et al*., 2012). The various cementing agents that may be used in the pelletisation process may differ in their solubility and the pellets may not dissolve efficiently due to this and consequently not have the desired neutralisation effect on the soil.

The addition of limestone to soils had also been found to increase the activity of soil microbes, which contributes to a higher soil organic matter conversion rate. Liming also influences

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flocculation and dispersion of clays in soil and therefore increases aggregation of the soil (Haynes and Naidu, 1998; Bronick and Lal, 2005). Soils that are adequately limed will enhance the sustainability of farming systems due to the higher yields that are obtained from crops, the lower production costs and a reduced pollution effect on the environment (Fageria and Baligar, 2008).

### 2.2.2 Gypsum and phosphogypsum

Gypsum may potentially be more effective to ameliorate subsoil acidity than the application of limestone (Ritchley *et al*., 1995). This method of ameliorating acidic soils did however have little success on less weathered soils with a similar pH (Farina *et al*., 2000). This is attributed to the higher solubility of gypsum, compared to limestone, which causes higher amounts of $Ca^{2+}$ to move down into the soil profile. Since gypsum is primarily used to improve saline soils, this secondary use is not widely used, and effectivity to ameliorate soil acidity may also vary.

A trial was done in Australia in order to investigate whether or not the use of phosphogypsum could ameliorate subsoil acidity (Smith *et al*., 1994). It was found that soil pH did not increase below the depth of 5 cm after 18 months have passed since the application was done (Smith *et al*., 1994). Crusciol *et al.* (2016) also evaluated the use of phosphogypsum to ameliorate acidic soils. Their findings were that regardless of the liming material used, the concentrations of exchangeable Ca were raised from the soil surface to a depth of 0.10 m three months after the treatments were applied. They did however find that 12 months after the application, the highest concentrations of exchangeable Ca were observed where phosphogypsum was used to address soil acidity.

### 2.2.3 Organic Compounds

It is hypothesised that the application of compost in combination with limestone application will promote the movement of $Ca^{2+}$ through the soil profile. This is proposed due to the complexation of $Ca^{2+}$ with organic acids such as fulvates, which are more soluble and more mobile than $Ca^{2+}$ on its own in solution, and this complex then transporting the $Ca^{2+}$ into the soil profile (Liu and Hue, 2001). Adequate amounts of water are however needed for these calcium fulvates to be transported deeper into the soil profile. It was found that most of the available calcium fulvates do not contain sufficient amounts of $Ca^{2+}$ to satisfy plant requirements or to raise the concentrations of $Ca^{2+}$ in soils that are deficient in $Ca^{2+}$ (Liu and

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Hue, 2001). It may also prove to be impractical to use these Ca-fulvates due to the high production cost and restricted availability.

**2.2.4 Calcium- and magnesium silicates**

The use of calcium- and magnesium silicates to ameliorate acidic soils has been evaluated, since silicate is 6.78 times more soluble than limestone ($CaCO_3$) and should therefore be able to reach the subsoil faster than limestone (Castro and Crusciol, 2013). They found that 12 months after application, limestone only raised the soil pH to a depth of 10 cm, whereas the calcium and magnesium silicates raised the soil pH to a depth of 20 cm. The combination of limestone and either a magnesium or calcium silicate applied to the surface improved the soil chemically to the deepest layer of the soil 12 months after the surface application was done. Their results indicated that limestone and the silicates decreased the concentrations of both $H^+$ and $Al^{3+}$ to a depth of 20 cm within 12 months of application. Their results also showed that 18 months after application, the silicate decreased the amount of $Al^{3+}$ toxicity to a depth of 60 cm, whereas the same effect of limestone on $Al^{3+}$ toxicity went to a depth of 40 cm. The cost and availability of these silicates might prevent the use thereof from being a viable option for some.

**2.3 Quality determining factors of limestone**

The quality of limestone is primarily determined by two factors, namely the chemical composition, also referred to as chemical purity, and the physical particle size, also referred to as fineness (Alley *et al*., 2005; Fageria and Baligar, 2008).

Fineness of the liming material correlates with the rate at which the limestone will neutralise acidity within the soil profile and it is stated that with increasing fineness of liming material, the surface area that can react with acidity also increases (Haby and Leonard, 2002, Fageria and Baligar, 2008). Haby and Leonard (2002) also found limestone that was grounded to pass through a 0.25 mm screen raised pH by the highest amount, whereas limestone that was 2 mm or larger in size had very little effect on ameliorating soil acidity. Particles of limestone that can pass through a 0.3 mm mesh are small enough to dissolve completely and are also considered to be 100% effective (Schwab *et al.*, 2007).

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A widely used method of expressing chemical purity is by expressing the reactivity of a liming material as a percentage of the acidity that the same amount of pure calcium carbonate would neutralise (Schwab *et al.*, 2007). This value is widely referred to as the calcium carbonate equivalence (CCE) of the liming material.

Apart from the two major factors, there are several others that may have an influence of the efficacy of limestone. Some of these factors are the moisture and Mg contents of the liming material as well as the temperature of the soil (Alley *et al*., 2005; Fageria and Baligar, 2008). Some countries also refer to an effective neutralising value (ENV) as a measure of the limestone quality (Fernández and Hoeft, 2009). The effective neutralising value is calculated by taking both the CCE and the fineness of the limestone material into account. The magnitude of pH alteration that is the result of limestone application positively correlates to the rate of liming, however the velocity at which the reaction occurs remains similar for different liming rates when the same limestone source is applied (Caires *et al*., 2005).

Increases in both soil temperature and soil moisture have been found to improve the rate of the neutralising reaction (Fageria and Baligar, 2008).

**2.4 Placement and physical incorporation of limestone**

The slow movement of lime into the soil profile is well known. In conventional systems, limestone is broadcasted and then physically incorporated into the soil. An alternative to conventional tillage is no-tillage, which is gaining popularity throughout various countries and production systems. This method of management entails restricting the physical disturbance of soil and directly planting crops in soils with as little disturbance as possible. Due to this increased adoption of no-tillage, the physical incorporation of limestone is not a viable option, since the physical disturbance doesn't fit within the no-tillage parameters set by the FAO (2020) which only allows vehicle traffic for planting and spraying. In places like the Western Cape of South Africa, where no-tillage is widely adopted, the slow movement of limestone into the soil profile provides uncertainty about possible management practices to effectively apply limestone.

In general, the chemical properties of a topsoil that is managed under no-tillage are more favourable than a topsoil managed under more conventional methods (Lal, 1997). Organic

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matter accumulates over time in soil and this leads to increased CEC of soils, which increases the concentration of exchangeable ions, even in acidic soils (Ernani *et al*., 2002; Caires *et al*., 1998). The resulting increase in CEC leads to soils holding more plant available nutrients and can therefore slow acidification of soils through preventing the leaching of basic cations. Where no-tillage principles are followed, the amounts of exchangeable $Mg^{2+}$, $Ca^{2+}$ and $K^{+}$ have been found to be significantly higher in the topsoil in comparison to those of a soil under more conventional practices (Sumner, 1995). One chemical property that is an exception, however, is soil acidity, where more acidity problems tend to manifest in the subsoil of soils managed under no-tillage and stratification of soil acidity may be present (Rahman *et al*., 2008). At the low pH of acidic soils, some plant nutrients become less available to plants, such as Ca and Mg, whereas the uptake of other nutrients increase at low pH, such as Cu, Zn, Fe and Mn (Fageria and Zimmermann, 1998). The solubility of Al also increases at low pH and can become toxic to plants in soils with a low pH (Foy, 1984). In soils where no-till is used, the pH of soils tends to be lower than soils where conventional principles are followed (Dick, 1983; Rahman *et al*., 2008). This observation could be the result of the increased soil OM in these soils, which also means that more organic acids are present in soils.

In no-tillage systems, liming of soil is done through surface application and the applied limestone is not incorporated into the soil (Rheinheimer *et al*., 2018). Thus, where no-tillage is followed, the pH of the subsoil tends to be unchanged by the limestone application, due to the slow downward movement of limestone into soil (Liu and Hue, 2001). Limestone application on the soil surface had been found to raise the pH of the topsoil in a relatively short amount of time but is slow to ameliorate acidity in the subsoil (Ernani *et al*., 2004). This is supported by Caires *et al.* (2008), who found that surface applied limestone in a no-tillage system took between eight and ten years to ameliorate subsoil acidity. They found that when compared to a control where no liming was done, the surface applied limestone significantly raised the soil pH and the concentrations of exchangeable $Ca^{2+}$, whilst the exchangeable $Al^{3+}$ and $Al^{3+}$ saturation decreased to a depth of 10 cm in after the first year following the limestone application. In a separate trial done, Caires *et al.* (2005) found that liming improved soil pH and decreased the amount of exchangeable Al to a depth of 10 cm in one year after liming and reached a depth of 20 cm 2.5 years after the surface liming was done. Though it is widely accepted that limestone moves slowly into the soil profile, it has also been stated that the

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downward movement of limestone deeper into soil is still poorly studied, especially in variable charge soils (Fageria and Nascente, 2014). This is ascribed to the limestone only reacting within the layer where it is applied, with acidity, Al toxicity and Ca deficiencies in the subsoil remaining unaddressed (Caires *et al*., 2006). Tiritan *et al*. (2016) has reported that despite the low solubility of limestone, there was a rapid reaction in the topsoil after a surface liming was done. Conversely, Joris *et al.* (2013) found that most of the limestone that is applied on the soil surface remains inert for a few years after application. This phenomenon was ascribed to the fact that some of the applied limestone neutralises acidity in the topsoil, which raises the pH, and in turn the soil conditions are unfavourable for the remainder of the applied limestone to react with the acidity in the topsoil. Cifu *et al.* (2004) found that liming only raised the concentrations of exchangeable $Ca^{2+}$ in the subsoil after all the exchange sites on the clay minerals in the topsoil had been saturated with the $Ca^{2+}$ ion. Auler *et al.* (2017) also found that the surface applied limestone, as well as the physically incorporated limestone, raised soil pH and the concentrations of both $Ca^{2+}$ and $Mg^{2+}$, whilst also reducing the amount of $Al^{3+}$ in the top 10 cm of soil. They did find however that only the physically incorporated limestone treatments showed this same trend to a depth of 20 cm. They also found that the methods of physical incorporation of limestone did not differ significantly to address the before mentioned factors in the soil. In a field trial done in Brazil, it was found that very low amounts of surface applied limestone reach below 5 cm from the surface, even after three years following the application of the limestone (Caires *et al*., 2008). Liu and Hue (2001) also found that only 7.6% of limestone applied reached the next 10 cm layer below the layer where the limestone was applied. Caires *et al*. (2006) found that the highest level of increase in soil pH was observed in the layer where limestone was applied and the increase in soil pH below the applied layer was significantly less. Where 1.5 t $ha^{-1}$ of high quality, fine limestone was applied on the surface, it took up to 4 years to reach a depth of 10 cm and even eight years after the application no effect was observed below that depth (Caires *et al*., 2008).

It has been proposed that the natural channels in soil that remain undisturbed in soils under no-till may contribute to deeper movement of limestone into soils due to the old root channels improving the transport of limestone through the soil (Rheinheimer *et al.*, 2018). It is also proposed that the channels that are the result of direct drilling may contribute to limestone movement into the soil profile through the improved hydraulic conductivity of the soil due to

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the channels that were made by direct drilling (Chan and Heenan, 1993). It is however difficult to quantify what effect these channels may have on limestone movement, as destructive analysis of soil is needed, which makes monitoring the movement of limestone over time difficult. Contrary to this, Baldock *et al.* (1994) proposed that the dispersion of surface applied limestone may obstruct the macropores and natural channels in the soil, due to the high concentration of limestone found in the top layer of soils where limestone was surface applied. Despite this, Baldock *et al.* (1994) also found that surface applied limestone led to a lower bulk density of soil, along with an increase in microporosity. The increase in microporosity that they observed had a greater effect on total porosity than the decrease in macroporosity. Therefore, the total porosity of the soil where limestone was surface applied was higher than the total porosities of the soils where limestone was physically incorporated. Even where high levels of rainfall were simulated, it was found that most of the Ca from the limestone that is applied, remains in the topsoil and very little Ca moves into the subsoil (Liu and Hue, 2001). Caires *et al.* (2008) also reported very slow movement of limestone into the subsoil, with very little limestone of a 3 ton $ha^{-1}$ surface application reaching a depth below 5 cm three years after the application was done. Conversely, Blevins *et al.* (1978) found that in a high precipitation area (over 1000 mm per year) limestone moved to a depth of 30 cm into the soil, but the rate of limestone applied was three times the requirement for that soil. In another trial, movement of the calcium from the applied limestone was observed to a depth of 20 cm and they also suggested that surface application of limestone is a viable option in order to address subsoil acidity (Conyers *et al*., 2003). Brown *et al.* (2008) also found that two years after limestone was broadcasted, a significant increase in soil pH was observed to a depth of 15 cm. The movement of surface applied limestone is influenced by several factors. The various different reported rates of surface applied limestone movement can be attributed to the rates of liming and limestone purity, type of soil, amount of time passed between soil samplings, climatic conditions, usage of other fertilisers, especially acidic fertilisers, and the cropping systems that are used (Caires *et al*., 2005).

At the depth at which nitrogen fertiliser is placed in direct-seeded soils, soil acidity develops at a faster rate in comparison with soils that are conventionally tilled (Mahler and Harder, 1984). This is attributed to the repeated placement of nitrogen fertiliser in the same area of soil, which raises the concentration of $NH_4^+$ in that part of soil and therefore contributes to

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soil acidity through the release of $H^+$ from the oxidation of $NH_4^+$. There is also no mechanical mixing of soil, which leads to the build-up of acidity in that layer of the soil. The physical mixing of the soil may contribute to the prevention of the build-up of high amounts of nitrogen in a specific depth zone within the soil.

In a trial done in Brazil, both the movement of bases downward into the profile and the neutralisation of soil acidity were the same between where limestone was applied on the surface and where limestone was incorporated to a depth 20 cm in the soil (Caires *et al*., 2006). In this same trial, they also found that incorporation of limestone to a depth of 0.2 m effectively neutralised acidity in the topsoil, but negatively affected the organic matter content of the soil. This incorporation of limestone was also found to be less economical than surface application of limestone. These varying results in downward movement of limestone into soil appears to be highly dependent on factors such as soil type and rainfall or irrigation. Castro and Crusciol (2013) stated that other factors that influence the effect that liming has on the subsoil include the liming rate, quality of the liming material, method of application and tillage regime followed. Conversely to the slow movement of limestone into soil, Crusciol *et al.* (2016) found that soil pH in both the 0-5 and the 5-10 cm depth increments increased three months after the limestone was applied. Elsewhere it was also found that surface application only raised the pH of the surface layers of the soil, with very limited or no change in soil pH occurring deeper than 20 cm (Pavan *et al*., 1984).

According to Scott *et al.* (1997) the best results for plant growth in the short term are obtained where limestone is incorporated into the soil. This statement is supported by Fageria and Baligar (2008) who stated that the maximal benefits are obtained from liming when the liming material is physically incorporated into the soil and that liming should be done before the crop is established. Where limestone was incorporated in a trial in southern Brazil, the base saturation, the concentrations of both $Ca^{2+}$ and $Mg^{2+}$ and soil pH were increased within two years of liming (Joris *et al*., 2016). In the same trial, the regression equation showed that the maximum reaction occurred two and a half years after incorporation of limestone. In a 15 year experiment done in China, it was found that the concentrations of exchangeable $Ca^{2+}$ and $Mg^{2+}$ increased over time with increased rates of liming, with the increase being much higher in the 0-20 cm depth increment than in the 20-60 cm depth increment (Cifu *et al*., 2004). In this trial

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in China, the increase in exchangeable Ca was mainly observed in the top 10 cm of the soil profile. Costa and Rosolem (2007) stated that the physical incorporation of limestone into the soil mixes soil and the liming material which results in a faster reaction rate. This can be ascribed to the greater surface area of soil that is in contact with the liming material. Conyers *et al.* (2003) has done a trial that supports this finding. In their trial in Australia, the soil pH in the 5-10 cm depth increment was significantly higher one year after liming in a soil where limestone was incorporated with a disc plough in comparison with soil where a surface liming was done (Conyers *et al*., 2003). They found that it took up to four years for the surface applied limestone to raise the pH in the 5-10 cm depth increment by the same amount that was achieved after one year following incorporation with a disc plough. The amelioration of subsoil acidity was found to be slower where limestone was applied on the surface, however the pH of the top 5 cm remained higher than the disc treatment throughout the four years. The surface applied limestone also maintained a greater difference in pH in the 0-5 cm depth range than the physically incorporated limestone eight years after liming was done (Conyers *et al*., 2003). This difference in soil pH in the top 5 cm can be ascribed to the fact that nearly all of the surface applied limestone remained near to the surface, whereas the incorporated limestone was more spread out over the depth of the soil. The surface applied limestone raised the pH of the topsoil more severely than the incorporated limestone, which reacted over a greater depth, but to a lesser degree than the surface applied limestone. It is also stated that the low solubility of limestone is responsible for the diminishing neutralisation effect of the limestone on soil acidity as soil depth increases (Ernani *et al*., 2004). Cookson *et al.* (2008) found that the type of tillage used to incorporate limestone into the soil showed no significant differences in soil pH at the 5-10 cm depth increment. Furthermore, the pH of the 0-5 cm depth increment was comparatively higher than the 5-10 cm depth increment for both the surface liming and where the limestone was incorporated using conventional tillage methods (Cookson *et al*., 2008). This indicates that even though limestone incorporation moves some of the limestone that was applied deeper into the soil, most of the neutralisation still occurs in the topsoil.

Soil pH of the topsoil decreases with an increase in soil disturbance through tillage action (Cookson *et al*., 2008). The usage of conventional tillage practices also leads to severe degradation of soils (Hobbs, 2007). Use of conventional tillage may have other detrimental

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effects on soil, depending on environmental factors. For example, tilling soils that are wet may cause clods that become hard through the drying process and thereby preventing the plant roots of reaching the nutrients inside the clod (Fernández and Hoeft, 2009). If this is done on acidic soils, where already low concentrations of basic cations are found, this may further restrict the availability of these basic cations to plant roots. Incorporation of limestone into the soil was also found to have a more severe detrimental effect on the amount of organic matter in the topsoil than that of a surface limestone application (Caires *et al*., 2006). The detrimental effect that the tillage action associated with limestone incorporation has on the organic matter content of the soil, can increase the amount of basic cations that leach from the soil profile (Lal, 1997). This is ascribed to the soil having a lower CEC due to the decreased organic matter content of the soil. In another trial, it was found that the rate at which the downward neutralisation of soil acidity occurs, as well as the rate at which bases move downward, were the same when limestone was applied to the surface compared to where limestone was incorporated into the soil to a depth of 20 cm (De Oliveira and Pavan, 1996). This indicates that the rate at which the downward neutralisation reaction occurs remains constant, regardless of the depth at which the limestone is placed. It should however be noted that the incorporated limestone reacts from a deeper starting depth than the broadcasted limestone. This downward neutralisation reaction is therefore an attribute of the liming material itself and not of the soil properties.

A severely limited effect on soil acidity was found below the depth at which the limestone was placed, even at an immensely high rate of 25 Mg $ha^{-1}$ that was incorporated to a depth of 50 cm (Farina *et al*., 2000). The lack of amelioration below the depth of placement at even such a large rate of application, further confirms that the effect of limestone on soil acidity is limited to the depth of placement.

The location, or placement, of limestone during application is not the sole roleplaying factor when it comes to the liming of soils. The number of applications also influence the effectivity of the amount of limestone applied. Splitting the application of limestone into two applications increases the effectivity of the limestone application due to less limestone wasted due to runoff of surface water, especially in high rainfall areas (Rheinheimer *et al*., 2018). Rheinheimer *et al.* (2018) also postulated that a single application of a large amount of

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limestone will decrease the reactivity of the limestone, due to the subsequent high pH of the surface layer where limestone is applied. This is due to the substantial increase in soil pH to a level above where limestone reacts with acidity in the soil. Farina *et al.* (2000) reached the conclusion that it is futile to attempt to address subsoil acidity problems by means of surface application of limestone.

An alternative to either surface application or the physical incorporation of limestone, is the band placement of a liming material within the furrows during the planting process. It has been stated that this method of limestone application may help to limit the potentially high cost of liming a field with a high limestone requirement (Wildey, 2003). In a trial done in Washington, an application rate of 220 kg $ha^{-1}$ was effective in reducing soil acidity to a depth of 10 cm in a single year after application. This method ensures the placement of liming material in or near the rooting zone of the crop. This method does however have to be applied annually, since the placement of the liming material is only within the crop rows and cannot neutralise soil acidity in a large area as with the broadcasting of liming material.

A trial was done by Caires *et al.* (2006) from 1999 to 2003 where various limestone applications were used as treatments and the change in soil pH was monitored over the span of five years (Table 2.1). The results from this trial also supports the findings of several other mentioned studies that state that surface-applied limestone raises the pH of the topsoil more effectively than physically incorporated limestone, however the subsoil acidity remains mostly unaddressed. Where limestone was physically incorporated, the pH of the subsoil raised to a higher level compared to where limestone was surface-applied and not incorporated into the soil. Two different treatments for surface application were included, with one being the full rate of limestone being applied in a single application, whereas the other surface-applied treatment entailed the splitting of the limestone rate into three separate applications and therefore one third of the limestone rate was applied annually over three years. Both surface applications performed similarly. It is therefore not recommended to split the application rate over three years, since the fuel and labour costs will be more expensive than applying the full rate in a single application and similar changes in soil acidity may be expected.

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**Table 2.1.** Changes in soil pH for different depths at 11 (1999), 23 (2000), 35 (2001), 48 (2002), and 60 (2003) months after various liming treatments. Table adapted from Caires *et al*. (2006).

| Depth (m) | Treatment | pH (0.01 mol $L^{-1}$ $CaCl_2$) | | | | |
|---|---|---|---|---|---|---|
| | | **1999** | **2000** | **2001** | **2002** | **2003** |
| 0-0.05 | No lime | 4.7 | 4.8 | 4.8 | 4.8 | 4.8 |
| | Surface-applied lime[a] | 5.0 | 5.4 | 6.2 | 6.1 | 5.9 |
| | Surface-applied lime[b] | 5.7 | 5.7 | 6.1 | 5.9 | 5.8 |
| | Incorporated lime | 5.5 | 5.6 | 5.7 | 5.6 | 5.5 |
| 0.05-0.10 | No lime | 4.7 | 4.7 | 4.7 | 4.6 | 4.6 |
| | Surface-applied lime[a] | 4.8 | 4.9 | 5.0 | 5.0 | 5.1 |
| | Surface-applied lime[b] | 4.8 | 5.1 | 5.0 | 5.2 | 5.3 |
| | Incorporated lime | 5.2 | 5.4 | 5.6 | 5.5 | 5.5 |
| 0.10-0.20 | No lime | 4.4 | 4.6 | 4.6 | 4.6 | 4.6 |
| | Surface-applied lime[a] | 4.5 | 4.8 | 4.7 | 4.7 | 4.8 |
| | Surface-applied lime[b] | 4.6 | 4.9 | 4.7 | 4.7 | 4.8 |
| | Incorporated lime | 4.7 | 5.0 | 5.2 | 5.3 | 5.2 |
| 0.20-0.40 | No lime | 4.2 | 4.5 | 4.5 | 4.6 | 4.5 |
| | Surface-applied lime[a] | 4.3 | 4.5 | 4.7 | 4.7 | 4.8 |
| | Surface-applied lime[b] | 4.4 | 4.5 | 4.7 | 4.7 | 4.9 |
| | Incorporated lime | 4.6 | 4.7 | 4.8 | 4.9 | 5.0 |

[a] One third of the lime rate applied per year on the surface for 3 years
[b] Full-rate lime on the surface in a single application

Caires *et al.* (2006) also measured the changes in Ca and Mg over the same amount of time, for the same depth increments (Table 2.2). Since the reaction of limestone with soil acidity releases Ca, increased concentrations of Ca in a specific layer of soil may indicate that limestone has reached the part of the soil where the Ca concentration has increased. The results from their field trial does indicate this trend, with the Ca concentration in the surface layer being much higher where limestone was surface applied compared to where limestone was incorporated. The concentrations measured in the subsoil are also as expected, with the incorporated limestone treatment showing higher amounts in the subsoil compared to the surface-applied limestone. The results from this trial also indicate that lime movement beyond the area of placement is slow and limestone may take several years to reach the subsoil. There were very little increases in the concentrations of $Ca^{2+}$ and $Mg^{2+}$ beyond the depth of incorporation, with values being slightly higher or similar to those of the surface-applied treatments beyond the 0.20 m depth.

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**Table 2.2.** Changes in exchangeable $Ca^{2+}$ and $Mg^{2+}$ (cmol+ $dm^{-3}$) for different depths at 11 (1999), 23 (2000), 35 (2001), 48 (2002), and 60 (2003) months after various liming treatments. Table adapted from Caires *et al*. (2006).

| Depth (m) | Treatment | Exchangeable $Ca^{2+}$ and $Mg^{2+}$ | | | | |
|---|---|---|---|---|---|---|
| | | **1999** | **2000** | **2001** | **2002** | **2003** |
| 0-0.05 | No lime | 5.60 | 5.50 | 5.70 | 6.17 | 6.20 |
| | Surface-applied lime[a] | 6.37 | 9.13 | 10.40 | 11.07 | 10.57 |
| | Surface-applied lime[b] | 8.27 | 9.80 | 9.60 | 10.53 | 10.57 |
| | Incorporated lime | 8.63 | 8.43 | 7.50 | 8.55 | 8.73 |
| 0.05-0.10 | No lime | 4.50 | 4.37 | 3.87 | 4.60 | 4.27 |
| | Surface-applied lime[a] | 4.60 | 6.13 | 5.80 | 6.33 | 6.07 |
| | Surface-applied lime[b] | 5.00 | 6.35 | 6.07 | 6.57 | 5.87 |
| | Incorporated lime | 7.07 | 6.92 | 6.48 | 7.95 | 7.53 |
| 0.10-0.20 | No lime | 2.83 | 3.27 | 2.27 | 3.63 | 3.07 |
| | Surface-applied lime[a] | 3.37 | 4.63 | 3.97 | 4.37 | 3.40 |
| | Surface-applied lime[b] | 3.10 | 4.70 | 3.53 | 4.40 | 3.07 |
| | Incorporated lime | 3.20 | 5.57 | 4.77 | 5.35 | 4.93 |
| 0.20-0.40 | No lime | 2.17 | 2.27 | 2.70 | 3.30 | 2.83 |
| | Surface-applied lime[a] | 3.00 | 2.97 | 2.87 | 3.97 | 3.17 |
| | Surface-applied lime[b] | 2.77 | 2.80 | 3.00 | 3.57 | 3.10 |
| | Incorporated lime | 3.60 | 3.33 | 3.07 | 4.50 | 3.37 |

[a] One third of the lime rate applied per year on the surface for 3 years
[b] Full-rate lime on the surface in a single application

## 2.5 Crop response to acidic conditions and the liming of soils

### 2.5.1 Crop sensitivity to acidity and the effect of acidity on the uptake of nutrients

As stated previously, crops differ in their sensitivity to acidity. Since the focus of this study was on barley (*Hordeum vulgare*), wheat (*Triticum aestivum*) and canola (*Brassica napus*), these three crops will be discussed in more detail towards the end of this chapter than other crops. Table 2.3 contains some of the popular, commercial field crops and their critical values of soil pH.

**Table 2.3.** Soil $pH_{(H2O)}$ values below which crop growth may be restricted (adapted from Ministry of Agriculture, Fisheries and Food, 1981, Appendix 2).

| **Crop** | **Critical Soil pH** |
|---|---|
| Field bean (*Vicia faba*) | 6.0 |
| Barley (*Hordeum vulgare*) | 5.9 |
| Sugar beet (*Beta vulgaris*) | 5.9 |
| Pea (*Pisum sativum*) | 5.9 |
| Oilseed rape/ Canola (*Brassica napus*) | 5.6 |
| Maize (*Zea mays*) | 5.5 |
| Wheat (*Triticum aestivum*) | 5.5 |
| Linseed (*Linum usitatissimum*) | 5.4 |
| Oats (*Avena spp.*) | 5.3 |
| Potato (*Solanum tuberosum*) | 4.9 |

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Aluminium toxicity, that is the result of acidic conditions in soils, is detrimental to the growth of plant roots, which may induce water stress in plants as well as impairing the uptake of nutrients by the roots (Caires *et al*., 2008). The alleviation of subsoil acidity may therefore lead to improved root development, which may lead to improved plant tolerance to water stress. Since limestone is a calcium containing compound, the application of this material will influence the concentration of Ca in soils over time. Since Ca and Mg have and antagonistic relationship in plant uptake, the change in Ca concentration that is the result of liming, may influence the uptake of Mg by crops (Fageria, 1974). The liming material of choice will further influence the uptake of these two cations, since the use of dolomitic limestone will add both $Ca^{2+}$ and $Mg^{2+}$ as cations to the soil solution, whereas calcitic limestone will only add $Ca^{2+}$ cations to the soil solution (Samtani *et al*., 2002).

The various nutrients within the soil solution differ considerably with regards to the pH's at which their availability to crops for uptake is the highest. Table 2.4 contains the optimum pH at which various plant nutrients are the most plant available:

**Table 2.4.** Optimum soil $pH_{(H2O)}$ values for the availability of the macronutrients and the most important micronutrients for most crops (adapted from Foth, 1990).

| N | P | K and S | Ca and Mg | Fe | Mn | B, Cu, Zn | Mo |
|---|---|---|---|---|---|---|---|
| 6-8 | 6.5-7.5 | >6 | 7-8.5 | <6 | 5-6.5 | 5-7 | >7 |

Calcium is necessary for structural roles in cell walls and membranes, it serves as a counter-cation for anions in the vacuole and for its role in the coordination of responses pertaining to challenges caused by the environment and developmental cues through concentration changes in the cytosol (Karley and White, 2009). Generally, the calcium requirements of most crops required for optimal metabolism and growth are low, however calcium is an important nutrient in maintaining nutrient balance and preventing potential toxicity within the plant (Fageria and Baligar, 2008). Deficiencies in calcium is generally observed as the membrane leakage of compounds with a low molecular weight, such as amino acids and sugars from the cytoplasm (Marschner, 1995).

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### 2.5.2 Canola response to liming

The insufficient concentrations of Ca and Mg, that are associated with acidic conditions, may lead to the development of deficiency symptoms in canola. Calcium deficiencies in canola can be observed as shoot tips and young leaves becoming hooked-shaped or dying off, whereas Mg deficiencies can be observed in the form of yellowing between leaf veins and the upwards curling and dying off of leaf margins in the later stages of Mg deficiency (Süzer, 2015).

It had been observed that the increased response of canola to liming was ascribed to the reduced amount of Al and Mn toxicities, rather than the canola being directly influenced by the limestone (Scott *et al*., 2003). In an Australian trial, it was found that liming of soil decreased the strength of the soil, which led to an increase in canola seedling emergence of 15% for every one unit increase in $pH_{(CaCl_2)}$ of the soil (Scott *et al*., 2003). This trial showed that the changes in the physical properties of soils, not just the more thoroughly researched changes in chemical properties, may influence crop response to liming.

### 2.5.3 Wheat and barley response to liming

In a long term trial in Western Australia, it was found that a limestone application of 2.5 t ha-1 on a soil with a $pH_{(CaCl_2)}$ of 4.6 in the 0-10 cm depth increment, led to 23-24% increases in overall yield of wheat (Tang *et al*. 2003). In the same trial, they found that the shoot biomass of barley increased by 45-70% on the plots where limestone was applied. In another trial done near Victoria in Australia, liming of a soil with $pH_{(H2O)}$ of 5.2 in the 0-10 cm depth increment led to an increase in grain yields of 31-103% (Coventry *et al*., 1986). The application of dolomitic limestone was also found to lead to increased concentrations of Mg in the leaves of wheat (Caires *et al*., 2002). This is to be expected since dolomitic limestone contains Mg and therefore the application thereof should raise the concentrations of plant available Mg in the soil solution.

Caires *et al*. (2006) found that surface application of limestone led to both increased quality and increased overall yield of wheat. The increased yield significantly related to the raised pH of the soil, as well as the increased concentrations of exchangeable $Ca^{2+}$ and the base saturation, as well as reduced concentrations of exchangeable $Al^{3+}$ in the soil. In a separate trial, both wheat and barley showed a positive linear relationship between yield and the increase of soil pH because of liming (Flower and Crabtree, 2011). In a south-eastern

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Australian trial, barley was the crop that showed the most positive response in yield to an increase in soil pH out of the following grain crops: barley, triticale and wheat (Liu *et al*., 2004). This was ascribed to barley being highly sensitive to soil acidity, more so than the other grain crops. Conversely, a Canadian trial found that application of limestone only improved the yield of barley at one of three sites and they also found that limestone application resulted in no improvement in wheat yield (Gupta *et al.*, 1978). This trial was done on podzolic soils, which have low concentrations of bases and are usually severely acidic and therefore these findings may have been the result of suboptimal amounts of other yield determining factors or potential toxicities due to the acidic conditions. Godsey *et al*. (2007) also found that liming had no significant increase in yield of winter wheat in a trial that was managed under no-tillage. The lack of increased yield may be due to the limestone not neutralising acidity in the rooting zone since the limestone was broadcast and not incorporated into the soil.

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## 2.6 Synopsis

With soil acidity occurring worldwide, and to different extents in various soil layers, addressing acidity could potentially improve crop productivity (Sumner and Noble, 2003). The rate of acidification in agricultural systems further emphasises the importance of effective limestone application. Acidification of soil can be aggravated naturally, for example acid rain or the leaching of basic cations, or through human intervention, particularly agricultural management such as the use of ammonium-based fertilisers (Fageria and Baligar, 2008; Goulding, 2016). Furthermore, with the increased adoption of no-tillage practices in annual cropping systems, acidity in soil may become stratified over time (Rahman *et al.*, 2008). The different chemical environments between the top-and subsoil, may potentially restrict root development and if the subsoil acidity is severe enough, yield penalties may result (Caires *et al*., 2008). Limestone application can be effective in neutralising soil acidity in agricultural landscapes. However, the effect may be limited to the area of placement of the limestone and therefore subsoil acidity may remain unaddressed in no-tillage systems where limestone is broadcasted on the soil surface and not physically incorporated (Liu and Hue, 2001; Caires *et al*., 2006; Rahman *et al*., 2008).

This literature review has underscored a lack of understanding of the extent of stratification of soil acidity in long-term no-tillage systems. There is also a lack of viable options that fit within the no-tillage guidelines in order to address subsoil acidity in no-tillage systems, where the topsoil is considered to be favourable to most crops.

The current study investigated the geographical spread and severity of the stratification of soil acidity in the long-term no-tillage production systems of the Swartland and southern Cape regions of the Western Cape Province of South Africa. This was done to investigate the extent of subsoil acidity in annual cropping production systems, since the literature is lacking with regards to the effect of long term no-tillage on the stratification of nutrients and soil acidity. The study also investigated the viability of a one-off strategic tillage, through the evaluation of chisel, disc and deep ripper ploughs in rotational cropping systems that incorporate canola and wheat. These tillage methods were evaluated in combination with two Class A limestone materials of differing chemical purities, as well as a pelletised limestone product.

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# Chapter 3: Determining the extent of soil acidity and pH stratification on long-term no-tillage soils across the Southern Cape and Swartland area

## 3.1. Introduction

Conservation agriculture (CA) is an effective strategy to improve the efficiency of production of crops (Smith *et al*., 2017; Findlater *et al*., 2019). No-tillage is an important part of CA, along with crop rotation and the maintenance of an organic soil cover. No-tillage entails disturbing less than 25% of the total cropped area or implementing soil disturbances that are less than 25 cm wide (FAO, 2014).

In the Western Cape Province of South Africa, more than 80% of farmers have converted to no-tillage systems (Smith *et al*., 2017). The implications of implementing no-tillage is that soil amendments, such as limestone (lime), cannot be mixed into the soil with tillage actions, as in the case of conventional agriculture. As soil has not been disturbed through tillage for several decades in this region, soil layers are expected to form with more nutrients skewed towards the soil surface, as well as pH stratification with increasing soil depth due to the relatively slow movement of lime (Barth *et al*., 2018). Surface broadcast lime was found to take up to a year to move only 5 cm down the soil profile of a loam soil that received 489 mm of rainfall (Miller, 2015) or five years to move 7.5 cm in a silty clay loam soil that received a mean annual rainfall of 739 mm over the five years (Godsey *et al*., 2007). In a study by (Conyers *et al*., 2003) it was found that it took between two and four years for 1.5 t $ha^{-1}$ of surface-applied lime to move to a depth of 10 cm in a clay loam soil that received 570 mm of rainfall. Acidity will thus only be neutralised to the depth that lime is able to move.

The southern Cape and Swartland regions of the Western Cape Province produce a large proportion of the country's wheat (*Triticum aestivum*) (> 50%), barley (*Hordeum vulgare*) (89%), and canola (*Brassica napus*) (100%) under dryland conditions (USDA, 2015; Mogala, 2017; De Kock, 2018). Wheat, barley, and canola are sensitive crops to acid soil conditions (Tang *et al*., 2003; Angus *et al*., 2008). Soil acidification results in decreased solubility or displacement of crop nutrients such as P, Ca, Mg, and K (Foy and Atkinson, 1991; Kunhikrishnan *et al*., 2016). More importantly, however, is that as the $pH_{(KCl)}$ of the soil decreases below 4.5, heavy metals such as Al become more soluble (Kochian, 1995). Toxic levels of Al causes, inter alia, stunting of crop roots (Krstic *et al*., 2012), thus limiting the uptake

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of water and nutrients and consequently crop growth and production. It also results in the displacement and subsequent leaching of essential basic cations from cation exchange sites. Soil acidity may be detrimental to microbial activity in soil, such as *Rhizobium* that are important for nitrogen fixation (Fageria and Baligar, 1999; Rousk *et al*., 2010) as well as bacteria that break down complex carbon structures and mineralise other nutrients (Robson and Abbott, 1989; Kunito *et al*., 2016). Acid soil conditions are thus limiting for crop growth as well as soil biology. Failing to address acidity within the soil profile will have a negative influence on sustainability of crop production systems.

Currently little is known regarding the extent to which the soils in southern Cape and Swartland regions are acid, or the extent of the occurrence of soil pH stratification. A lack of knowledge regarding the state of soils in these production regions with regards to soil acidity restricts addressing this crop-growth limitation. Therefore, a soil-sampling survey was conducted, taking soil samples at 0 – 5, 5 – 15 and 15 – 30 cm depths from fields that have been under no-tillage for at least eight years. The soil samples were taken at three depth increments with the purpose of identifying the change in soil acidity with depth, while identifying whether there is an association with other soil attributes and explanatory variables. Explanatory variables included region, soil texture, rainfall, and years since last liming. The final objective was thus to determine the extent and geographical spread of soil acidity and pH stratification throughout the southern Cape and Swartland production regions in the Western Cape Province of South Africa, as well as possible causes thereof.

## 3.2. Materials and Methods

### 3.2.1. Description of Climate, Soil Types, and Land Use of the Survey Sites

For the purpose of the survey, the Western Cape Province was separated into two regions according to differences in rainfall distribution and soil type, namely the southern Cape and Swartland regions (Figure 3.1). Both regions have a Mediterranean-type climate. The timing of rainfall differs between the two regions, with the majority (about 80%) of the rainfall in the Swartland occurring from April to October, and the majority of the rainfall in the southern Cape (roughly 60% in the eastern districts and 75% in the western districts) occurring from April to October. The areas surrounding the following towns within the southern Cape region were sampled: Albertinia, Riversdale, Heidelberg, Witsand, Swellendam, Riviersonderend,

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Bredasdorp, Napier, Caledon, and Greyton. The annual mean rainfall for these areas ranged from 300 – 550 mm annually and the mean temperature is 17 – 18°C for all these areas. The areas surrounding the following towns were sampled in the Swartland: Malmesbury, Riebeek Kasteel, Gouda, Moorreesburg, Koringberg, Piketberg, and Porterville. The annual mean rainfall for these areas ranges from 300 – 600 mm and mean temperatures are 18 – 19°C.

The soils in both regions are classified as soils with minimal development, usually shallow and on hard or weathering rock, with or without intermittent diverse soils (Western Cape Department of Agriculture, 2020). The soils in the Swartland are also red and yellow, massive or weak structured soils, with low-to-medium base status (Western Cape Department of Agriculture, 2020).

In terms of land use, similar crops are cultivated in both regions, due to both regions having Mediterranean-type climates. Both regions are mostly under dry-land wheat, barley, oats, canola, and lupin (Lupinus spp.) production. Various forage crops are incorporated into crop rotation systems to support livestock production. The preferred forage crops by southern Cape farmers generally include lucerne (Medicago sativa), whereas the Swartland farmers tend to cultivate annual Medicago spp. (mostly M. trancatula and M. polymorpha).

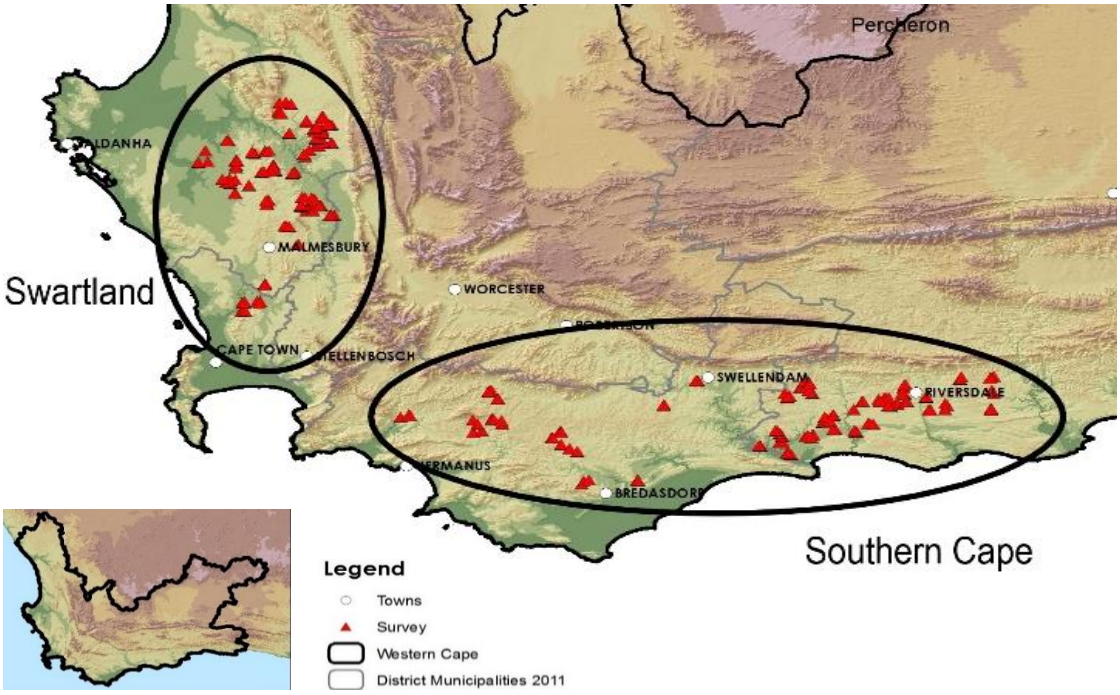


**Figure 3.1.** A map indicating the surveyed area, which included the southern Cape and Swartland regions of the Western Cape Province of South Africa.

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### 3.2.2. Sampling and Analyses

The survey was conducted by means of soil samples accompanied by questionnaires (Appendix B) relating to system management and liming history. The questionnaires were completed by each farmer who participated in the survey to obtain information regarding liming methods, liming history, and the crop history of the fields that were sampled.

For a respective field to be surveyed, the following criteria had to be met: (i) The field had to be managed under no-tillage for at least eight years prior to sampling for the survey; (ii) no liming should have been done on the respective fields in the current year of surveying (2019); (iii) the crop rotation system used by the farmer had to include either wheat, barley, or canola. Two hundred and fifty-three fields were sampled across the Western Cape Province. At each field, six soil cores (4 cm diameter) were taken at depths of 0 – 5, 5 – 15, and 15 – 30 cm and composited per depth increment. Soil analyses included exchangeable base cations (K, Ca, Mg, Na), soil $pH_{(KCl)}$, exchangeable acidity, and electrical resistance according to the methods described by Non-Affiliated Soil Analysis Work Committee (1990). Chemical analyses of pH were done in a 1:2.5 soil: KCl solution, and of exchangeable acidity and base cations with a potassium chloride and citric acid solution, respectively (Non-Affiliated Soil Analysis Work Committee, 1990). The standard procedures of Non-Affiliated Soil Analysis Work Committee (1990) were used for the determination of cation-exchange capacity (CEC; ammonium acetate). Electrical resistance was determined by the method described by (United States Salinity Laboratory Staff, 1954). These soil chemical attributes were analysed at the three respective depths in order to determine the presence of nutrient or acidic stratification between the depth increments as well as to identify possible reasons for why acidity could be present in the soil.

In 15 of the fields where canola was planted in 2019, leaf samples were taken at physiological maturity to investigate relationships between soil nutrients, and nutrient uptake by crops. Leaf samples were taken of the youngest mature leaves shortly before flowering. Canola was chosen as the crop to analyse, since its requirement for various nutrients is higher than the other crops in the rotation systems. Calcium deficiencies are sometimes observed in the region on canola, but not for other crops (Personal communication, G.A. Agenbag, 2018). Therefore, if soil conditions are deteriorating due to acidification, canola would be the most

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likely crop in the system to show deficiencies first. The Ca concentrations in the leaves of the canola could thus be a further indication of the acid status of the soil.

### 3.2.3. Data Analyses

Descriptive statistics including mean, maximum, minimum, median, and standard deviation were calculated for samples for both the Swartland and southern Cape combined, as well as separately for the two regions. We used the standard deviation as an indicator of the variability of soil properties. Groups of correlated variables were defined for by using a factor analysis to reduce the number of variables and to detect structure in the relationships between soil chemical properties. Latent variables for each group of soil chemical properties were created by normalising (varimax rotation) and averaging variables from each factor for which the eigenvalues of the correlation matrix were one or greater.

Analysis of variance for acid soil response variables and factor loadings were performed with mixed models incorporating the Kenward–Roger degrees-of-freedom method (Kenward and Roger, 2009). This method adjusts the estimator in computation of the Satterthwaite-type correction of the covariance matrix to account for heteroscedasticity. Soil depth was specified as the fixed effect and field as the replicated random effect. A Bonferroni post-hoc test was performed to compare soil parameter means across depths. Subsequently, fields with soil $pH_{(KCl)}$ values lower than 5.5, the optimal threshold for most crops, were identified and separated into a subset for further analyses, and analysed using the Kenward-Roger method as described above. STATISTICA software version 13 was used to conduct the statistical analyses (TIBCO Software, 2020).

## 3.3. Results and Discussion

Figure 3.2 shows the distribution of soil $pH_{(KCl)}$ for samples from the Swartland and southern Cape regions of South Africa, as well as individually for each region. Farmers aim for a soil $pH_{(KCl)}$ of 5.5, so a $pH_{(KCl)}$ distribution where the majority of observations are around 5.5 is to be expected. More samples from the Swartland region had a $pH_{(KCl)}$ lower than 5.0 than the southern Cape region.

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The $pH_{(KCl)}$ stratification trend observed in both areas (Table 3.1) showed a decrease (from 0 – 5 to 5 – 15 cm) followed by an increase (from 5 – 15 to 15 – 30 cm) in $pH_{KCl}$ with increasing depth.

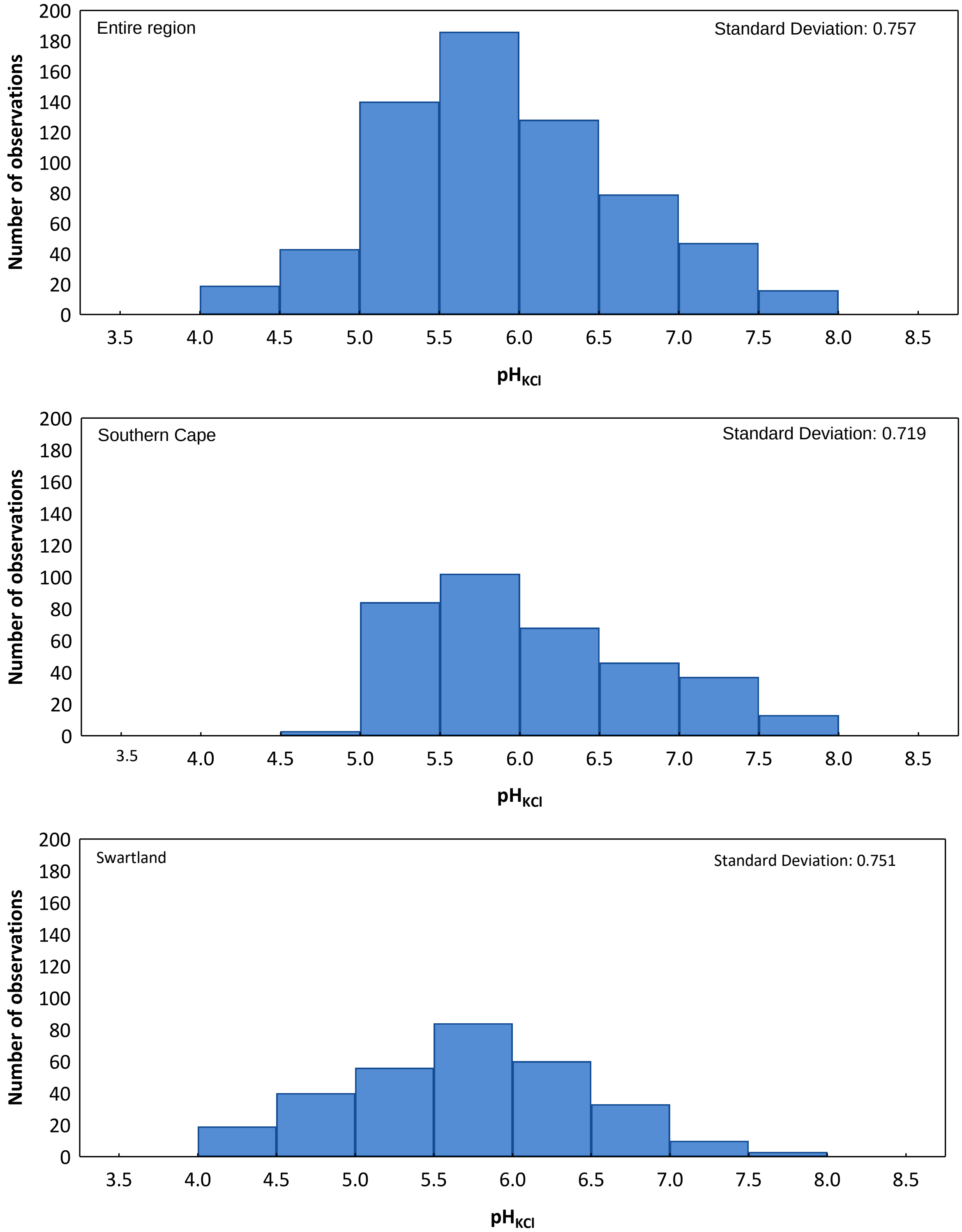


**Figure 3.2.** The mean soil $pH_{(KCl)}$ distribution for all samples (**top**) as well for the southern Cape (**middle**) and the Swartland (**bottom**) regions separately.

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**Table 3.1.** Descriptive statistics of soil chemical attributes between three depths (0 – 5, 5 – 15 and 15 – 30 cm) for soils sampled in the southern Cape and Swartland regions. SD = standard deviation.

| | n | | | Mean | | Median | | Minimum | | Maximum | | SD | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Southern Cape | Swart-Land | Depth (cm) | Southern Cape | Swart-Land | Southern Cape | Swart-Land | Southern Cape | Swart-Land | Southern Cape | Swart-Land | Southern Cape | Swart-Land |
| $pH_{(KCl)}$ | 118 | 99 | 0 – 5 | 6.2 | 6.0 | 6.2 | 6.1 | 4.8 | 4.5 | 7.5 | 7.4 | 0.64 | 0.69 |
| | 115 | 106 | 5 – 15 | 6.0 | 5.5 | 5.9 | 5.6 | 5.0 | 4.2 | 7.7 | 7.6 | 0.70 | 0.73 |
| | 115 | 100 | 15 – 30 | 6.2 | 5.8 | 5.8 | 5.7 | 5.1 | 4.1 | 7.9 | 7.9 | 0.87 | 0.76 |
| Ca (mg kg $^{-1}$) | 118 | 99 | 0 – 5 | 2514 | 1728 | 1761 | 1390 | 430 | 344 | 12898 | 10134 | 2193 | 1473 |
| | 115 | 106 | 5 – 15 | 1857 | 985 | 1127 | 763 | 366 | 116 | 9634 | 8562 | 1818 | 1007 |
| | 115 | 100 | 15 – 30 | 1818 | 658 | 889 | 545 | 326 | 106 | 11644 | 3798 | 2339 | 550 |
| Mg (mg kg $^{-1}$) | 118 | 99 | 0 – 5 | 241 | 255 | 206 | 218 | 46 | 53 | 679 | 888 | 116 | 150 |
| | 115 | 106 | 5 – 15 | 201 | 141 | 173 | 119 | 41 | 18 | 481 | 408 | 99 | 81 |
| | 115 | 100 | 15 – 30 | 247 | 148 | 190 | 124 | 60 | 17 | 1463 | 720 | 182 | 107 |
| Exchangeable Acidity ($cmol_c$ kg$^{-1}$) | 118 | 99 | 0 – 5 | 0.13 | 0.18 | 0 | 0 | 0 | 0 | 1.30 | 1.39 | 0.33 | 0.40 |
| | 115 | 106 | 5 – 15 | 0.19 | 0.39 | 0 | 0 | 0 | 0 | 1.22 | 1.54 | 0.35 | 0.46 |
| | 115 | 100 | 15 – 30 | 0.12 | 0.24 | 0 | 0 | 0 | 0 | 1.00 | 1.12 | 0.28 | 0.36 |
| Acid saturation (%) | 118 | 99 | 0 – 5 | 1.49 | 2.64 | 0 | 0 | 0 | 0 | 15.53 | 23.00 | 3.78 | 5.88 |
| | 115 | 106 | 5 – 15 | 2.72 | 8.17 | 0 | 0 | 0 | 0 | 17.44 | 44.16 | 5.07 | 10.38 |
| | 115 | 100 | 15 – 30 | 2.00 | 6.51 | 0 | 0 | 0 | 0 | 16.63 | 44.65 | 4.56 | 10.71 |

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The increase in soil $pH_{(KCl)}$ from the 5 – 15 to the 15 – 30 cm depth could be due to the 15 – 30 cm depth increment having the natural $pH_{(KCl)}$ of that specific soil, which is related to base status of the parent material (Grieve, 1999). The differential depth effect between the southern Cape and Swartland could possibly be due to the acid component of the effective cation exchange capacity (ECEC) of the Swartland soils being higher than that of the southern Cape soils. The parent material and physical attributes, such as texture, of the soils that differ between the Swartland and southern Cape regions may further account for the differences in $pH_{(KCl)}$ and exchangeable acidity, since ECEC depends highly on the texture of a soil (Fooladmand, 2008). Soils containing more clay or organic matter will have a greater ECEC. These soils will thus have a greater capacity to hold basic cations leading to a greater buffering capacity against pH change compared to sandy soils with a lower ECEC (Nathan, 2020). It was, however, found that soil texture had no effect ($p > 0.05$) on $pH_{(KCl)}$ and exchangeable acidity (Table 3.3). This result may be due to a disproportionate number of samples being from a sandy-loam texture class (Table 3.4).

Stratification could possibly be attributed to the higher ($p \leq 0.05$) concentrations of basic cations found in the 15 – 30 cm depth increment compared to the 5 – 15 cm depth increment (Table 3.3). Basic cations can be leached downward through the soil profile and accumulate in the subsoil on top of impervious layers that prevent the complete loss of these cations. Clay particles tend to accumulate deeper in the soil profile, and the higher ECEC of these particles is able to hold more basic cations and therefore have a greater resistance to change in pH compared to the sandy soil in the shallow depth increments (Jacobsen, 1997; Sumner and Miller, 1996).

It is clear that the degree of pH stratification in the Swartland is more severe than in the southern Cape. A higher degree ($p \leq 0.05$) of pH stratification was observed between the three respective soil depths of the Swartland soils, especially between the 0 – 5 and 5 – 15 cm depths (Tables 3.1 and 3.3). Despite the abrupt change of $pH_{(KCl)}$ from the topsoil to the subsoil, the subsoil $pH_{(KCl)}$ was not lower than the optimal $pH_{(KCl)}$ for most crops. According to the South African fertiliser guidelines, the optimal $pH_{(KCl)}$ for wheat is 5.0, and for barley and canola 5.5 (FERTASA, 2016). Other sources report an optimal $pH_{(CaCl2)}$ of 5.5 for most crops (Gazey and Davies, 2009; Miller, 2020), which is equivalent to an approximate $pH_{(KCl)}$ of 5.2 (Van Lierop, 1981).

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**Table 3.2.** Principal component extraction using factor analysis. Varimax-normalised factor loadings for soil chemical properties across the Western Cape crop production region in South Africa are presented, along with the eigenvalue, total variance, and cumulative variance. Boldfaced values indicate the highest loading of each soil attribute, therefore forming part of a particular factor.

| Soil Chemical Properties | Factor 1 | Factor 2 | Factor 3 | Factor 4 |
|---|---|---|---|---|
| **$pH_{(KCl)}$** | 0.465 | 0.073 | **0.747** | 0.060 |
| **Electrical resistance (Ohm)** | −0.021 | **−0.628** | −0.183 | −0.498 |
| **Electrical conductivity (mS $m^{-1}$)** | −0.036 | **0.787** | 0.072 | 0.433 |
| **Exchangeable acidity ($cmol_c$ $kg^{-1}$)** | −0.110 | −0.057 | **−0.941** | −0.056 |
| **Ca (mg $kg^{-1}$)** | **0.919** | −0.070 | 0.165 | 0.225 |
| **Mg (mg $kg^{-1}$)** | **0.690** | 0.543 | 0.172 | −0.101 |
| **Na (mg $kg^{-1}$)** | 0.052 | **0.829** | 0.0531 | −0.160 |
| **K (mg $kg^{-1}$)** | 0.194 | 0.072 | 0.154 | **0.766** |
| **P (mg $kg^{-1}$)** | 0.131 | 0.009 | 0.009 | **0.719** |
| **Effective cation exchange capacity ($cmol_c$ $kg^{-1}$)** | **0.944** | 0.042 | 0.151 | 0.212 |
| **Acid saturation (%)** | −0.126 | −0.172 | **−0.916** | −0.146 |
| **Eigenvalue** | 5.302 | 2.072 | 1.632 | 1.426 |
| **Total variance (%)** | 40.8 | 15.9 | 12.6 | 10.7 |
| **Cumulative variance (%)** | 40.8 | 56.7 | 69.3 | 80.2 |

**Table 3.3.** ANOVA F statistics and *p* values for the fixed effects in the mixed models of soil of depths (0 – 5, 5 – 15, and 15 – 30 cm), region (Swartland vs. southern Cape), annual rainfall, soil texture, and years since previous liming. ECEC = Effective cation exchange capacity.

| **Factor** | **Factor 1** | | **Factor 2** | | **Factor 3** | | **Factor 4** | |
|---|---|---|---|---|---|---|---|---|
| **Variables** | Ca, Mg, ECEC | | Electrical Resistance, Conductivity, Na | | $pH_{(KCl)}$, Exchangeable Acidity, Acid Saturation | | K, P | |
| | **F** | ***p*** | **F** | ***p*** | **F** | ***p*** | **F** | ***p*** |
| **Depth** | 14.25 | < 0.001 | 16.21 | < 0.001 | 12.06 | < 0.001 | 306.59 | < 0.001 |
| **Region** | 18.85 | < 0.001 | 0.01 | 0.938 | 12.62 | 0.001 | 8.24 | 0.004 |
| **Rainfall** | 3.32 | 0.001 | 0.39 | 0.924 | 6.33 | < 0.001 | 3.43 | 0.001 |
| **Texture** | 2.37 | 0.070 | 12.84 | < 0.001 | 1.71 | 0.166 | 0.57 | 0.636 |
| **Years since liming** | 0.92 | 0.500 | 0.73 | 0.667 | 0.98 | 0.451 | 1.69 | 0.103 |

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**Table 3.4.** Percentage of soil samples per texture class.

| Texture | Percentage of Samples | | |
|---|---|---|---|
| | All Samples | Southern Cape | Swartland |
| **Sandy loam** | 89.13 | 92.55 | 85.20 |
| **Sand** | 9.04 | 7.45 | 10.86 |
| **Sandy clay loam** | 1.68 | 0 | 3.62 |
| **Clay** | 0.15 | 0 | 0.32 |

The mean $pH_{(KCl)}$ of all three soil depths in the southern Cape was suitable to produce wheat, barley, and canola. A slight $pH_{(KCl)}$ stratification was observed between the three soil depths of the soils sampled in the southern Cape, with the highest $pH_{(KCl)}$ in the region being 7.9 and the lowest being 4.8 (Table 3.1). The mean $pH_{(KCl)}$ of all three of the respective soil depths in the southern Cape were also optimal for wheat, barley, and canola production.

The trend observed for exchangeable acidity was as expected, when compared to the trend of $pH_{(KCl)}$ over increasing depth. In both regions the 5 – 15 cm depth increment had higher ($p \leq 0.05$) amounts of exchangeable acidity than the 0 – 5 and 15 – 30 cm depth increments (Tables 3.1 and 3.3). It is as expected that the depth increment with the lowest $pH_{(KCl)}$ also has the highest amount of exchangeable acidity. The mean exchangeable acidity in the 5 – 15 and 15 – 30 cm depth increments in the Swartland was more than double the amount in the same depth increments of the southern Cape. The maximum values of exchangeable acidity in the Swartland were higher in all three depth increments than the corresponding values of the southern Cape region. The difference in exchangeable acidity between the two regions may be ascribed to the higher ($p \leq 0.05$) amounts of Ca in the southern Cape soils than the Swartland soils (Tables 3.1 and 3.3). This corresponds to findings that showed that increases ($p \leq 0.05$) in the Ca content of soils correspond with decreases in the exchangeable acidity, specifically the Al component (Whitten *et al.*, 2000). The relationship between high concentrations of Ca and lower amounts of exchangeable acidity in the soil may help to identify soils in other regions that are similarly managed, that may develop exchangeable acidity problems over time. This could especially be the case if the soils naturally contain low concentrations of Ca.

A clear difference ($p \leq 0.05$) in acid saturation for both regions was observed (Tables 3.1 and 3.3). The acid saturation for all three depths in the Swartland were higher ($p \leq 0.050$ than the corresponding depths in the southern Cape (Table 3.3). The mean acid-saturation percentages

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of both the 5 – 15 and the 15 – 30 cm depths in the Swartland were over three times the values of the corresponding depths in the southern Cape (Table 3.1). The mean value for the 5 – 15 cm soil depth in the Swartland was also above the 8% threshold given by (Dang *et al.*, 2015), which is unfavourable for wheat production. The maximum acid saturation for all three depths of the Swartland soils were higher than the corresponding values in the southern Cape. The maximum acid saturation for all three depths in the Swartland were also above the 8% threshold value given for wheat. Furthermore, barley and canola are less tolerant to soil acidity than wheat, and therefore these acid saturation values in the Swartland may be even more restricting to these crops than to wheat (Foy, 1996; DAFF, 2016; DAFF, 2016b).

The mean Ca concentrations in the Swartland soils (Table 3.1) were low for crop production in the top 0 – 15 cm of the soil profile and very low at the 15 – 30 cm depth when compared to the relative concentrations for crop production (Table 3.5). Furthermore, the minimum and maximum Ca concentrations reported in these soils were very low and very high respectively for crop production. The mean Mg concentration throughout the 0 – 30 cm of the soil profile in the Swartland soils were suitable for crop production. The minimum Mg concentrations ranged from low (0 – 5 cm depth) to very low (5 – 15 cm and 15 – 30 cm depth), while the maximum Mg concentrations reported were relatively high throughout the 0 – 30 cm.

The mean Ca concentration in the 0 – 15 cm soil depth in the southern Cape soils was suitable for crop production in general (Table 3.5). However, the minimum Ca concentrations reported for the southern Cape soils were too low for crop production whilst the maximum concentrations ranged from high (15 – 30 cm depth) to very high (0 – 5 and 5 – 15 cm depth). The mean Mg concentrations in the southern Cape soils were suitable for crop production throughout the soil profile (0 – 30 cm). The minimum Mg concentrations were low at all three depth intervals and the maximum concentrations were high (0 – 5 and 5 – 15 cm depth) to very high (15 – 30 cm depth).

Both Ca and Mg are important macronutrients for plant growth and development, however different crops have varying requirements. Canola, for example, has twice the demand for Ca than wheat (Norton, 2013). Furthermore, well-structured soils generally have more than twice as much Ca than Mg (Botta, 2015). Both Ca and Mg play an important role in soil aggregate stability (Magdoff, 1993) and Ca helps maintain a nutrient balance within the soil (Parnes,

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2013). Furthermore, Ca is essential for maintaining the structural integrity and expansion of cell walls and lipid membranes (Schlecht *et al.*, 2006). Calcium plays an important role in osmoregulation and internal signalling within the plant cells. Magnesium on the other hand forms part of the chlorophyll molecule and is thus essential in the photosynthetic processes within plants (Magdoff, 1993). Magnesium also plays a role in the metabolism and movement of sugar in plants, which is essential for their growth and development.

**Table 3.5.** Ca (mg kg$^{-1}$) and Mg (mg kg$^{-1}$) concentrations in the soil for crop production (Hazelton and Murphy, 2007).

| | Ca (mg kg$^{-1}$) | Mg (mg kg$^{-1}$) |
|---|---|---|
| **Very low** | < 400 | < 36 |
| **Low** | 400 – 1000 | 36 – 120 |
| **Moderate** | 1000 – 2000 | 120 – 360 |
| **High** | 2000 – 4000 | 360 – 960 |
| **Very high** | > 4000 | > 960 |

The availability of nutrients such as Ca and Mg to plants is influenced by the soil pH. As the soil pH decreases, the $H^+$ and $Al^{3+}$ that become more soluble under these pH conditions displace basic cations such as Ca and Mg from the cation exchange sites on the soil particles, leading to the basic cations being leached down the soil profile where they are not available for plant uptake (Kunhikrishnan, 2016).

The mean Ca concentration of the southern Cape soils was higher ($p \leq 0.05$) for all three depth increments than the Ca concentrations of the Swartland soils, with the mean concentration in the 15 – 30 cm depth increment being nearly three times that of the Swartland soils (Tables 3.1 and 3.3). The higher ($p \leq 0.05$) Ca concentrations reported in the southern Cape soil compared to the Swartland soils could be attributed to the soil parent material of the southern Cape being of a more calcareous nature (White and Holland, 2018). Soils with a higher $pH_{(KCl)}$ are expected to generally have a greater Ca concentration (Norton, 2013), which could also explain the higher ($p \leq 0.05$) Ca concentration in the southern Cape soils compared to the Swartland soils, which had a lower mean $pH_{(KCl)}$ (Table 3.1). Although the criteria for sampling a field in the survey included no lime applications in the last year prior to sampling, relatively recent lime applications (one to three years before sampling) could potentially explain the high Ca concentrations reported in the maximum values of both the Swartland and southern

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Cape Ca concentrations (Espinoza *et al*., 2006). It was however found that there was no relationship ($p > 0.05$) between Ca and Mg concentrations in the soil and the number of years since the previous lime application was done (Table 3.3). The mean Mg concentrations did not show the same trend as Ca. The Swartland soils had higher ($p \leq 0.05$) concentrations of Mg in the 0 – 5 cm depth increment and the southern Cape soils had higher concentrations in the 5 – 15 as well as the 15 – 30 cm depth increment (Table 3.3). The addition of dolomitic lime on soils already high in Mg concentration could explain the high Mg concentrations reported in the maximum values of both regions' soils. Sandy textured soils with a low ECEC are more vulnerable to low Ca and Mg concentrations due to greater risk of being leached down the soil profile and could form part of the soils that were reported as having minimum Ca and Mg concentrations in both regions (Magdoff, 1993). It was found that texture did not influence ($p \geq 0.05$) Ca and Mg concentrations in the soils (Table 3.3). As stated earlier, this result may be due to the disproportionate number of samples being in the same texture class and therefore an inaccurate correlation between soil texture and Ca and Mg concentrations could have been obtained (Table 3.4).

It was found that rainfall only influenced ($p \leq 0.05$) Factor 1 (concentrations of both Ca and Mg as well as the CEC of soils) as such that increased rainfall was associated with increased loadings of Factor 1 (results not shown). Although higher annual rainfall could result in leaching of Ca and Mg, higher rainfall can be associated with a higher CEC of soils as a result of a higher content of soil organic matter (Magdoff, 1993; Schlecht, 2006). Rainfall did not influence ($p > 0.05$) Factor 3, which is linked to soil acidity aspects.

### 3.1 Subset Data from Fields with $pH_{(KCl)} \leq 5.0$ at Any Depth Increment

Of the total number of samples taken at all three depths across the survey, 19.3% of the samples from the Swartland had a $pH_{(KCl)} \leq 5.0$ and 6.2% ≤ 4.5 (Figure 3.3, Table 3.6). For the soils where at least one depth increment had a $pH_{(KCl)} \leq 5.0$, the 5 – 15 cm depth had a $pH_{(KCl)}$ that was lower ($p \leq 0.05$) than the 0 – 5 depth increment (Figure 3.3) and the exchangeable acidity (Table 3.7) was higher ($p \leq 0.05$) than that of the 0 – 5 cm depth increment (Table 3.3). The $pH_{(KCl)}$ and acidity of the 0 – 5 and the 15 – 30 cm depth increments were more similar than the 0 –5 and 5 – 15 cm depth increments. The change in $pH_{(KCl)}$ from the 0 – 5 to the 5 – 15 cm depth increment is severe enough for the rooting depth to become limited, due to the

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5 – 15 cm depth increment being below the threshold $pH_{(KCl)}$ values for most crops (FERTASA, 2016).

**Table 3.6.** Percentage of samples per depth for each region with $pH_{(KCl)} \leq 5.0$.

| Depth (cm) | Southern Cape (%) | Swartland (%) |
|---|---|---|
| 0 – 5 | 0.00 | 11.11 |
| 5 – 15 | 1.74 | 29.25 |
| 15 – 30 | 0.87 | 17.00 |
| Total | 0.86 | 19.30 |

Figure 3.3 showed that for the soils where at least one of the depth increments had $pH_{(KCl)} \leq 5.0$, there was a decrease ($p \leq 0.05$) in $pH_{(KCl)}$ from the 0 – 5 to the 5 – 15 cm depth increment. The 15 – 30 cm depth increment did not, however, differ ($p \leq 0.05$) from the 0 – 5 cm depth increment. Soil $pH_{(KCl)}$ of below 5.0 is a growth limitation for barley, wheat, and canola (FERTASA, 2016). The stratification shown in Figure 3.3 indicates that the change in soil $pH_{(KCl)}$ is severe enough in these soils to possibly become a growth limitation to barley, wheat, and canola. The acid soil layer in a soil profile becomes a limitation for plant growth, ultimately decreasing the effective rooting depth. A decrease in the effective depth that roots can grow in a soil profile could impact crop production. In the study by (Hirzel and Matus, 2013), it was reported that grain yield, plant height, and number of stems per meter of wheat were affected by the depth of the soil profile. In this study, grain yield was up to 37% higher in deep soils compared to shallow soils. Furthermore, there are various reports (Busscher *et al*., 2001; McDonald, 2006; Christopher *et al*., 2008; Whitmore and Whalley, 2009) stating that increases in effective soil depth for root growth improved the productivity and yield of maize (*Zea mays* L.), wheat, and barley. The positive effect of soil depth on crop productivity could be attributed to the increased ability of roots to take up nutrients and water at greater soil depths (Richards, 2008). Whereas in shallow root systems, nutrients such as N can leach beyond the shallow root zone and be lost from the system (Thorup-Kristensen, 2006). The concentrations of Ca and Mg in the 0 – 5 cm depth increment were higher ($p \leq 0.05$) than in both the 5 – 15 and 15 – 30 cm depth increments (Table 3.7). Stratification of nutrients such as Ca and Mg with increasing soil depth can be expected in long-term no-tillage soils (Dang *et al*., 2015; Ismail *et al*., 1994; Rahman *et al*., 2008).

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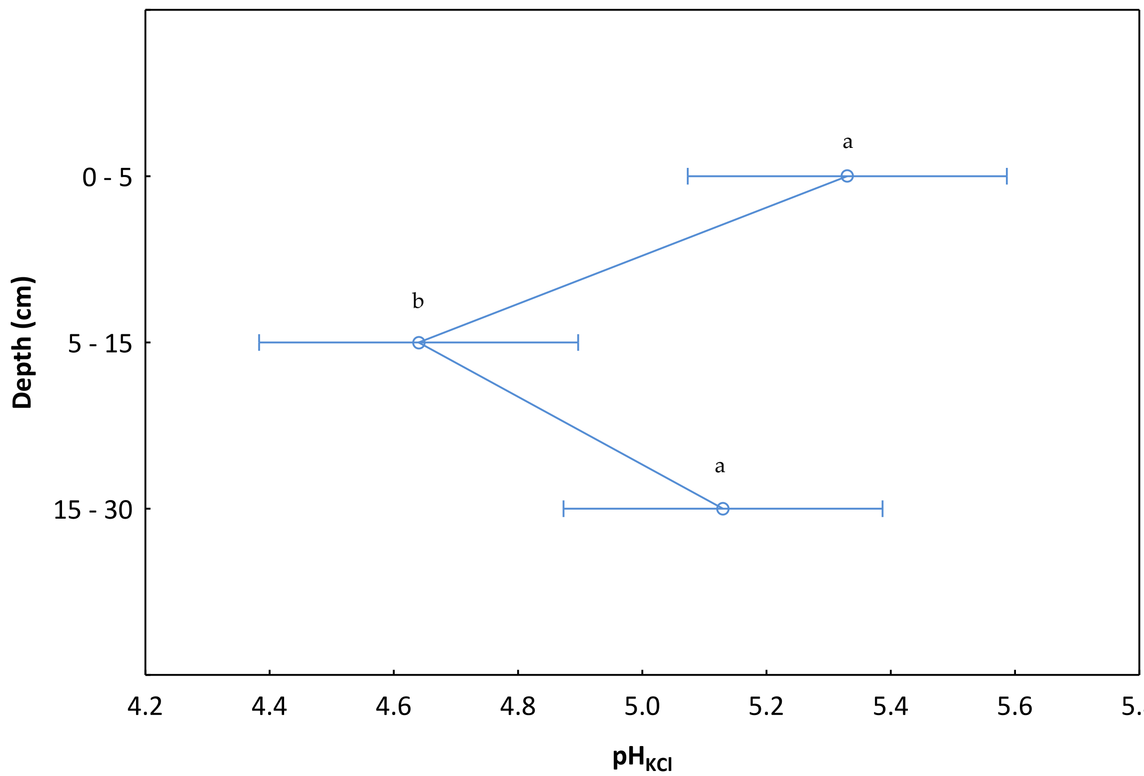


**Figure 3.3.** Stratification of $pH_{(KCl)}$ between 0 – 5, 5 – 15, and 15 – 30 cm soil depth of soils with at least one depth increment with $pH_{(KCl)} \leq 5.0$. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

**Table 3.7.** F-and *p* values of $pH_{(KCl)}$ Ca (mg $kg^{-1}$), Mg (mg $kg^{-1}$), exchangeable acidity (cmolc $kg^{-1}$), and acid saturation (%).

| | F Value | *p* Value |
|---|---|---|
| **$pH_{(KCl)}$** | 7.76 | < 0.001 |
| **Ca (mg $kg^{-1}$)** | 13.58 | < 0.001 |
| **Mg (mg $kg^{-1}$)** | 6.88 | < 0.001 |
| **Exchangeable acidity (cmolc $kg^{-1}$)** | 3.59 | 0.040 |
| **Acid saturation (%)** | 6.13 | 0.040 |

Figures 3.4 and 3.5 indicate that the base status of the topsoil (0 – 5 cm) is higher ($p \leq 0.05$) than that of the deeper depth (5 – 15 and 15 – 30 cm) increments (Table 3.8). Figure 3.4 and Figure 3.5, respectively, show the relationship between depth and the ECEC and depth and acid saturation and not exchangeable acidity. These trends in base status and exchangeable acidity correspond with Table 3.1, which indicates that the $pH_{(KCl)}$ of the 5 – 15 cm depth increment was the lowest of the three sampling depths, since low $pH_{(KCl)}$ corresponds with high levels of exchangeable acidity.

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**Table 3.8.** Mean values of various soil measurements for the three depth increments. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

| Soil Depth (cm) | Exchangeable Ca (mg $kg^{-1}$) | Exchangeable Mg (mg $kg^{-1}$) | Exchangeable Acidity (cmol $kg^{-1}$) |
|---|---|---|---|
| 0 – 5 | 1039 a | 188 a | 0.68 ab |
| 5 – 15 | 535 b | 103 b | 0.95 a |
| 15 – 30 | 417 b | 149 b | 0.56 b |

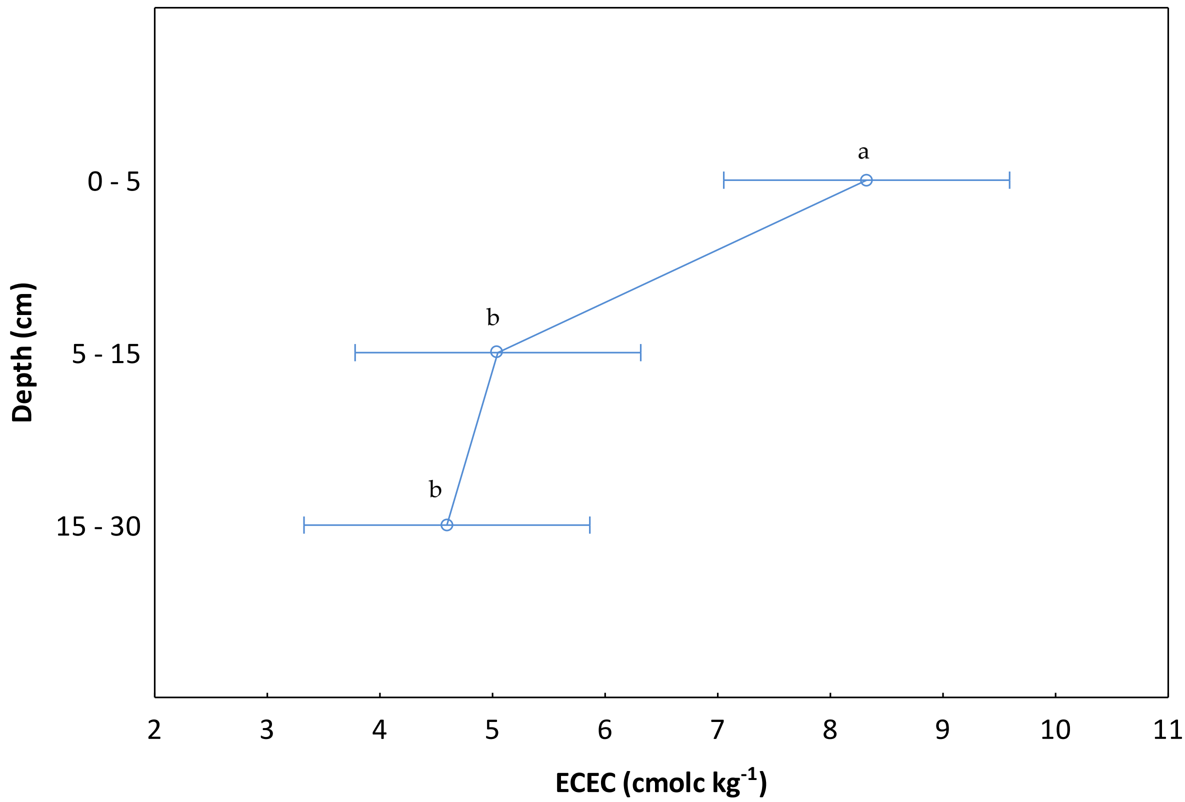


**Figure 3.4.** ECEC between 0 – 5, 5 – 15, and 15 – 30 cm soil depths of soils where at least one depth increment had $pH_{(KCl)} \leq 5.0$. ECEC = Effective cation exchange capacity. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

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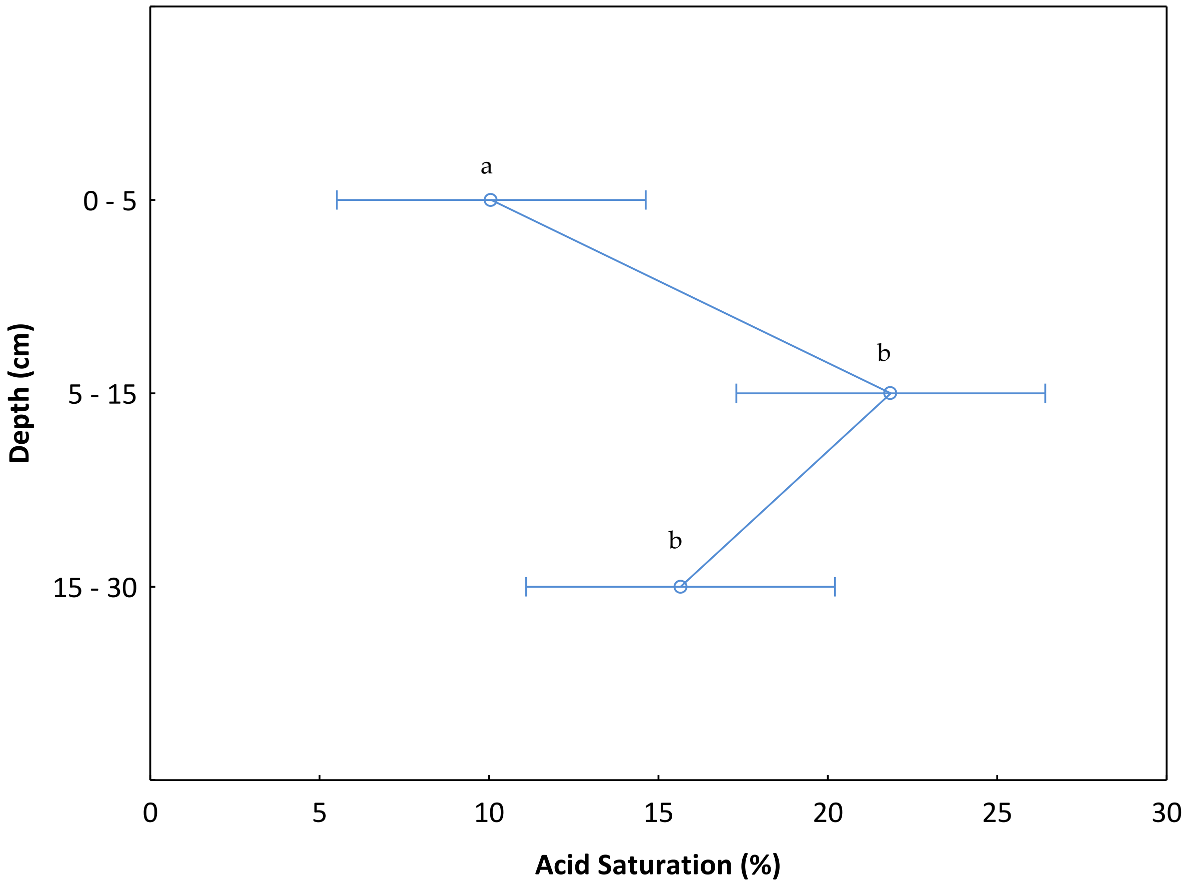


**Figure 3.5.** Stratification of acid saturation between 0 – 5, 5 – 15, and 15 – 30 cm soil depths of soils where at least one depth increment had $pH_{(KCl)} \leq 5.0$. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

### 3.2. Canola Leaf Nutrient Content

Table 3.9 shows that of the 15 fields included in the survey where canola was cultivated, the leaf samples averaged above both the Canadian, South African, and USA threshold values for all the nutrients measured (FERTASA, 2016; Canola Council of Canada, 2017; Campbell, 2000). Some individual samples did, however, contain suboptimal amounts of B, even though the mean value is above the threshold values of the Canadian and USA standards, whilst also being within the range for the South African standard. It is standard practice for farmers who cultivate canola to apply leaf sprays in the growing season to apply B. The results from the leaf analyses that were done for this survey support this practice that farmers are already implementing.

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**Table 3.9.** Sample means of analysed canola leaf nutrients in comparison with the Canadian, USA, and South African (RSA) threshold values for each nutrient. *n* = 15; standard deviation is indicated in parenthesis.

| | **N (%)** | **P (%)** | **S (%)** | **Ca (%)** | **Mg (%)** | **K (%)** | **Fe (mg kg$^{-1}$)** | **Cu (mg kg$^{-1}$)** | **Mn (mg kg$^{-1}$)** | **Zn (mg kg$^{-1}$)** | **B (mg kg$^{-1}$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample mean | 5.46 (0.62) | 0.53 (0.11) | 0.83 (0.10) | 4.28 (1.24) | 0.86 (0.38) | 4.10 (2.10) | 250.99 (185.28) | 6.76 (5.55) | 74.02 (27.94) | 33.45 (6.58) | 30.28 (12.71) |
| Canadian threshold | 2.40 | 0.24 | 0.24 | 0.49 | 0.19 | 1.40 | 19.00 | 2.60 | 14.00 | 14.00 | 29.00 |
| USA threshold | 3.60 | 0.37 | 0.47 | 1.60 | 0.10 | 2.15 | 82.00 | 4.00 | 20.00 | 28.00 | 20.00 |
| RSA threshold | 3.50 | 0.3 – 0.6 | 0.50 | 1.4 – 3.0 | 0.2 – 0.6 | 2.20 | 50 – 300 | 3 – 5 | 30 – 200 | 20.00 | 20 – 50 |

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### 3.3. Recommendations

Incorporating a one-off strategic tillage every few years in which surface-broadcast lime is incorporated into the soil profile could be a possible solution to the $pH_{(KCl)}$ stratification (with an acid subsoil) that occurs in these long-term no-tillage soils. One-off strategic tillage in no-tillage systems has been found to be effective in alleviating nutrient stratification in the soil (Kettler *et al*., 2000; Quincke *et al*., 2007). One-off tillage can thus be considered to redistribute the higher Ca and Mg concentrations that occur near the soil surface in both the Swartland and southern Cape soils. Furthermore, research done by (Quincke *et al*., 2007b, Baan *et al*., 2009; Crawford *et al*., 2015; Leygonie, 2016; Liu *et al*., 2016; Van Zyl, 2017; Dang *et al*., 2018; Conyers *et al*., 2019) has shown that conducting a one-off tillage in soils that have been under no-tillage has no significant negative impact on soil physical and chemical attributes or on grain yield. It was reported by (Whitten *et al*., 2000; Caires *et al*., 2006; Caires *et al*., 2011; Tiritan *et al*., 2016) that incorporating lime into the soil (at varying depths, methods, and rates) was successful in alleviating subsoil acidity.

The relatively low Ca concentrations of the soils sampled in both the Swartland and southern Cape regions could be addressed through the addition of soil amendments such as gypsum [$Ca(SO_4)$] or lime (Norton, 2013). The application of gypsum can be considered on the soils with a suitable $pH_{(KCl)}$ for crop production but a low concentration of Ca. Gypsum which constitutes of about 22% Ca will allow for an increase in the Ca concentration of the soil without increasing the soil $pH_{(KCl)}$ (due to its lack of carbonates), however it is more commonly used on sodic soils.

In the case of an acid soil, the addition of lime can be used to rectify soil acidity whilst addressing low Ca concentrations in the soil. Furthermore, in acid soils where the Mg concentration is low, as in the case of the minimum values reported for the Mg concentrations of both the Swartland and southern Cape soils, the application of dolomitic lime may be considered. The addition of dolomitic lime will enable soil acidity to be addressed as well as increasing the Ca and Mg concentrations in the soil.

### 3.4. Conclusions

Although the mean $pH_{(KCl)}$ across the entire surveyed area (Swartland and southern Cape) was of little concern in terms of crop production, a large portion (19.3%) of soils (specifically in the

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Swartland) had at least one depth increment with $pH_{(KCl)} \leq 5.0$, which is below the optimal values for barley, wheat, and canola production. Furthermore, a change ($p \leq 0.05$) in soil acidity was observed over increasing depth, indicating stratification of acidity. It was also found that soil depth, annual rainfall of the region as well as the region itself, had an influence ($p \leq 0.05$) on Ca, Mg, pH, exchangeable acidity, and the acid saturation of the soil. The mean acid saturation in the 5 – 15 cm depth increment in the Swartland was above the 8% threshold value for wheat production. Due to barley and canola being less tolerant to soil acidity than wheat, however, these acid-saturation values may be more restricting to the production of these crops.

Of the fields that contained at least one depth increment with pH ≤ 5, higher amounts ($p \leq 0.05$) of acidity were found in the 5 – 15 cm depth increment, where lime evidently was not able to neutralise acidity in no-tillage systems. Therefore, crop yield is expected to be negatively affected by acid soil conditions on 19.3% of Swartland soils. The significant stratification of soil acidity and Ca and Mg observed between soil layers needs to be addressed. Strategic one-off tillage may address the stratification of both soil acidity and nutrients, such as Ca and Mg, and could therefore be considered as a viable option to incorporate into the management of no-tillage production systems.

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# Chapter 4: The Effects of Various Forms, Purities and Fineness of Liming Materials and Various Physical Soil Disturbances on Soil Properties and the Crop Responses of Canola and Wheat

## 4.1 Introduction

There are various strategies and products available to ameliorate soil acidity problems. In conventional agriculture, ground agricultural limestone is applied on the soil surface with a lime-spreader and followed by physical incorporation into the soil by a tillage action. Conversely, limestone application in no-tillage systems is done through the application of the liming material on the soil surface, with no physical incorporation (Rheinheimer *et al.*, 2018). The limited movement of limestone through soil profiles over time may lead to the development of stratification of soil acidity and subsequently acidity in the subsoil remains unaddressed by the limestone application (Bescansa *et al.*, 2006, Ernani *et al.*, 2004, Garcia *et al.*, 2007).

Various limestone products are available commercially, with liming materials differing in chemical purity, particle size, and form (e.g., granules or pellets). Limestone quality affects the reaction time and efficiency of neutralisation, and is primarily determined by the chemical composition, or chemical purity, and the particle size, or fineness (Alley *et al*., 2005; Fageria and Baligar, 2008). The choice of liming material to be applied could have definite impacts on soil chemistry. Price of various products also differ, and that of pelletised products can be significantly higher than standard Class A lime, and therefore the choice of liming material may also have financial implications for the farmer. The different liming materials available may differ in effectiveness and method of application.

The practice of doing a one-off tillage every few years in a no-tillage regime is gaining popularity and it was found to have no significant detrimental effects on soil health and crop productivity (Azam and Gazey, 2020; Labuschagne *et al.*, 2020). With this practice gaining popularity, there are also questions raised regarding which type of tillage action is the most effective to incorporate liming materials into soils. Questions are also raised regarding which combination of liming material and type of tillage is the most efficient at addressing soil acidity throughout the entire profile. The aims of this study were to determine the effect of form, fineness, and placement of limestone, with and without soil disturbance, on a) soil chemical attributes and b) the growth and development of canola (*Brassica napus L.*) and wheat (*Triticum aestivum*).

## 4.2 Materials and Methods

### 4.2.1 Description of research site

This study was conducted near Caledon (-34.270114, 19.492265), in the southern Cape region, Western Cape Province, South Africa (Figure 4.1). This is a region where wheat, canola and barley are produced commercially under dryland conditions.


**Figure 4.1.** Map of the Western Cape and the location of the research site used in this study (Mycape, 2020).

### 4.2.2 Soil

The soils in the Caledon region are classified as having minimal development, usually shallow on hard or weathering rock, with or without intermittent diverse soils (CapeFarmMapper, 2020). In the South African soil classification system, the soils are classified as poorly developed, shallow shale-derived soils with a high coarse fragment proportion. Glenrosa,

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Oakleaf and Swartland soils are the most common soils in the region (Soil Classification Working Group, 1991).

### 4.2.3 Climate

This region has a Mediterranean-type climate, with the majority of the rainfall occurring from April to October. The long-term mean for the region is 545 mm of rainfall annually. Figure 4.2 shows the monthly rainfall and mean daily temperatures per month for 2019 and 2020 at the trial site in comparison with the long-term means.

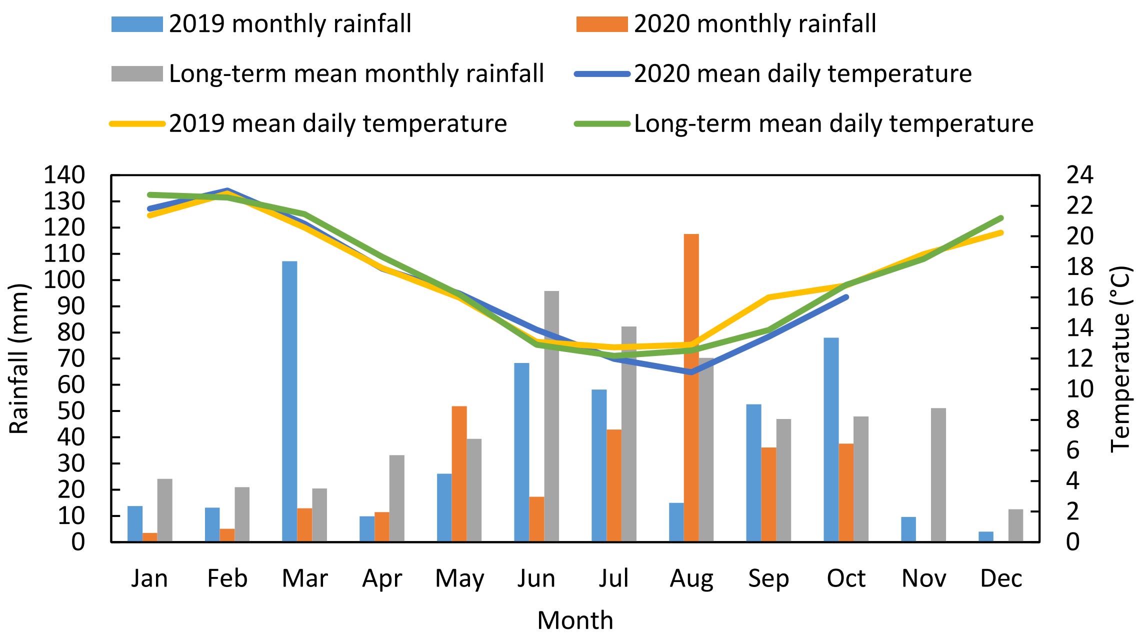


**Figure 4.2.** Monthly rainfall and mean temperatures for 2019 and 2020 at the trial site against the long-term mean monthly rainfall and daily temperature values.

### 4.2.4 Experimental design and treatments

The trial was a randomised block design, with four replicates and ten treatments (Table 4.1), i.e., 40 experimental units. Each plot had dimensions of 20 m x 4.5 m. Treatments consisted of a type of liming material, or lack thereof for the control, and a type of soil tillage, since it is known that lime reacts slowly to neutralise soil acidity (Ernani *et al*. 2004; Liu and Hue, 2001). The treatments were only conducted in the first year, but treatment effects were monitored over two growing seasons. Canola was planted in 2019 and wheat in 2020. The target soil $pH_{(KCl)}$ was 5.5 and the lime requirement according to a representative composite soil sample of the entire trial site prior to the start of the trial, was 1500 kg $ha^{-1}$. The Eksteen method was used to determine lime requirement (Eksteen, 1969).

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**Table 4.1.** Description of the soil disturbance, liming material, placement of liming material and liming rate of each treatment.

| Nr | Treatment code | Soil disturbance | Liming material | Placement of liming material | Liming rate |
|---|---|---|---|---|---|
| 1 | Control | No-till seed-drill only | None | - | - |
| 2 | Pel(saving)* | No-till seed-drill only | 93% CCE micro-fine calcitic lime, pelletised with molasses | Surface applied before crop establishment and the remainder was placed in row by the no-till seed-drill | 40 kg $ha^{-1}$ in rows and 1175 kg $ha^{-1}$ surface applied |
| 3 | Pel(BC) | No-till seed-drill only | 93% CCE micro-fine calcitic lime, pelletised with molasses | Surface applied | 1500 kg $ha^{-1}$ |
| 4 | Pel(IR) | No-till seed-drill only | 93% CCE micro-fine calcitic lime, pelletised with molasses | Placed in row through no-till seed-drill | 40 kg $ha^{-1}$ |
| 5 | Pel(IR+BC) | No-till seed-drill only | 93% CCE micro-fine calcitic lime, pelletised with molasses | Surface applied before planting and the remainder was placed in row by the no-till seed-drill | 40 kg $ha^{-1}$ in rows and 1460 kg $ha^{-1}$ surface applied |
| 6 | DS(95) | No-till seed-drill only | 95% CCE Class A calcitic lime | Surface applied | 1500 kg $ha^{-1}$ |
| 7 | DS(88) | No-till seed-drill only | 88% CCE Class A calcitic lime | Surface applied | 1500 kg $ha^{-1}$ |
| 8 | Rip(88) | Deep rip plough (300 mm deep, loosening of subsoil) | 88% CCE Class A calcitic lime | Surface applied and then incorporated with deep rip plough | 1500 kg $ha^{-1}$ |
| 9 | Chisel(88) | Chisel plough (200 mm deep, loosens large area of topsoil) | 88% CCE Class A calcitic lime | Surface applied and then incorporated with chisel plough | 1500 kg $ha^{-1}$ |
| 10 | Disc(88) | Disc plough (150 mm deep, inverts soil) | 88% CCE Class A calcitic lime | Surface applied and then incorporated with disc plough | 1500 kg $ha^{-1}$ |

*For this treatment, the liming rate was 19% less than the recommended rate, following the results of Jones and Mallarino (2018) for the application of micro-fine lime pellets.

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### 4.2.5 Crop establishment and crop management

Canola (cv. Hyola 559 TT) was established with a 5 row Equalizer seed-drill on the 14th of May in 2019. The seed density of the planting was 3 kg ha$^{-1}$ and row spacing was 300 mm. In 2020, wheat (cv. SST 056) was planted at a rate of 90 kg ha$^{-1}$ with row spacing of 270 mm.

Soil samples were taken prior to the onset of the trial. This was done to determine the lime requirement of the soil, as well as to determine which other nutrients should be applied, if necessary. There were differences ($p \leq 0.05$) between the Ca content, $pH_{(KCl)}$, ECEC between some of the plots, prior to the application of the treatments. These differences in soil chemical properties could be ascribed to in-field heterogeneity, which is common in the Western Cape soils. During the planting of canola, 3.5 kg of N, 14 kg of P, 7 kg of K and 4 kg of S was applied per hectare. The first top dress fertiliser application was done 14 days after emergence and 50 kg of N, 5 kg of P, 15 kg of K and 12 kg of S was applied. The second top dress was done at the beginning of the stem elongation phase. The second top dress was 35 kg of N and 4.5 kg of S per hectare. With the second top dress, a B liquid fertiliser, was applied at 150 g L$^{-1}$. Prior to establishment of wheat, 71 kg of N, 5 kg of P and 12 kg of K was applied. During the planting process, 9 kg of N, 12 kg of P and 3 kg of K was applied through the seed-drill. One topdressing was done four weeks after emergence, where 20 kg of N and 9 kg of K was applied.

### 4.2.6 Data collection

*4.2.6.1 - Soil parameters*

Soil samples were taken at four sampling intervals over the two growing seasons; prior to crop establishment in 2019, 90 days after the treatments were applied, after harvesting was completed in 2019, and in mid-2020, three weeks after crop emergence. Soil samples were taken at depths of 0 - 5, 5 - 15 and 15 - 30 cm, with at least four samples taken at each depth increment to form a representative sample for each plot. Samples were taken at different depth intervals to be able to detect any stratification of nutrients or acidity that may occur. An additional set of soil samples were taken for treatments that included placement of liming material within the crop rows. Samples were taken in the crop rows and between of the crop rows separately at the sampling done 90 days after treatments were applied and after harvesting was completed. The crop rows in 2020 differed from the rows in 2019, therefore sampling in-row could not have been done as in 2019. Standard chemical tests ($pH_{(KCl)}$, exchangeable acidity, Ca, Mg, Na, K, P, electrical resistance and ECEC) were performed on all

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soil samples according to the methods described by the Non-Affiliated Soil Analysis Work Committee (1990) and the United States Salinity Laboratory Staff (1954). A 1:2.5 soil: KCl solution was used for pH analysis. A 1M KCl solution was used to determine exchangeable acidity and a 1% citric acid solution was used to determine the exchangeable base cation contents of the soil samples (Non-Affiliated Soil Analysis Work Committee, 1990).

*4.2.6.2 - Plant parameters*

*Canola*

Plant population was determined four weeks after emergence. This was done by counting plants in ten randomly selected 1-m row lengths per plot. The average number of plants per plot was then used, along with the row spacing, to calculate the population ($m^{-2}$) using Equation 1.

$$\frac{\text{Seedlings m}^{-1}}{\text{Row spacing of seed-drill (m)}} = \text{Seedlings m}^{-2} \qquad \text{(Equation 1)}$$

The leaf area index (LAI) was determined at 30, 60 and 90 days after emergence (DAE) and aboveground biomass was determined at 30, 60, 90 and 150 DAE. Ten plants were extracted at random from each plot for analysis. At 30 DAE root biomass was also determined to compare crop establishment of the various treatments. The roots were washed and dried for 72 hours at 60$^{o}$C and weighed. For determining LAI, the leaves of each plant were carefully removed, and the leaf areas were measured using a Li-Cor LI 3100C Area Meter. The leaf area index of each plot was subsequently calculated using the plant populations of each respective plot. After the LAI for the individual plots had been determined, all of the aboveground material was dried for 72 hours at 60°C. After drying, the plant material was weighed on an Avery Berkel TA 602-2A scale to determine the dry mass. The aboveground biomass of each plot was subsequently calculated using the plant populations of each respective plot. The dry masses were then used to calculate the biomass in kilograms per hectare using Equation 2.

$$\frac{\text{Dry mass (g)} \times 0.0001 \times \text{plant population (plants m}^{-2}) \times 10\,000}{\text{number of plants taken} \times 1000} = \text{Biomass (kg ha}^{-1}) \qquad \text{(Equation 2)}$$

At the final biomass sampling (150 DAE), the number of side branches per plant was counted for canola. The number of seeds per pod were also counted.

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Canola was directly harvested on the 24th of October 2019. Harvesting was done with a Hege 140 harvester. Since ploughs require some forward movement to dig into the soil and to start disturbing the soil, the first 3 m of each plot was not harvested to eliminate any inconsistencies between the treatments. The harvested seeds were sieved through a 2 mm sieve to remove contaminants. The seeds harvested from each plot were weighed separately on a Scalerite Micro T2 platform scale and yield was calculated to tons per hectare using Equation 3.

$$\frac{\text{Harvested seeds (kg)} \times 10\,000}{1\,000 \times 17 \times 3} = \text{t ha}^{-1} \qquad \text{(Equation 3)}$$

Thousand seed weight (TSW) was determined, with seed counting paddles being used to randomly obtain and count 1000 seeds per plot. The 1000 seeds were weighed on an Avery Berkel TA 602-2A scale to determine the TSW. A sieved sample of the canola harvest from each plot was analysed with a Near-infrared Spectrometer (NIR) to determine the moisture content (%) and oil content (%) for each plot.

Harvest Index was calculated with Equation 4.

$$\frac{\text{Seed yield (kg ha}^{-1})}{\text{Aboveground biomass at 150 DAE (kg ha}^{-1})} = \text{Harvest Index} \qquad \text{(Equation 4)}$$

*Wheat*

Plant population was determined four weeks after emergence, also using Equation 1 and the same method as described for canola.

LAI was determined at 60 and 90 DAE and aboveground biomass was determined at 60, 90 and 150 DAE. This was done by randomly cutting three 1 m strips at ground level of each plot. Subsequently, all of the aboveground material was dried for 72 hours at 60°C. After drying, the plant material was weighed on an Avery Berkel TA 602-2A scale to determine the dry mass. The dry masses were then used to calculate the biomass in kilograms per hectare using Equation 2.

At the final biomass sampling, the number of ear-bearing tillers per meter were counted for wheat. This was done by randomly placing a 1-m rod in each plot and counting the number of ears on each tiller along the length of the rod. This was done four times for each plot.

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Wheat was harvested directly on the 10th of November 2020. Harvesting was done with a Hege 140 harvester. The harvest from each plot was sieved and weighed on a Scalerite Micro T2 platform scale and yield was calculated to tons per hectare using Equation 3. Thousand kernel weight (TKW) was determined for wheat by using a Numigral seed counter machine to count 1000 kernels and the 1000 kernels were weighed on an Avery Berkel TA 602-2A scale to determine the TKW. A sieved sample of the wheat harvest from each plot was also analysed with a NIR, which determined the moisture content (%), dry protein content (%), wet gluten content (%) and hectolitre mass (kg $hL^{-1}$). As for canola, the harvest index was determined for wheat using Equation 4.

#### 4.2.7 Statistical Analyses

Analysis of variance (ANOVA) was performed for crop production variables using the Kenward-Roger degree-of-freedom approximation methodology for mixed models (Kenward *et al.*, 1997). To account for heteroscedasticity, this method adjusts the estimates in such models using restricted maximum likelihood (REML) procedure. Block was specified as replicated random effect and treatment was specified as the fixed effect. Least Significant Difference (LSD) post-hoc tests for multiple comparisons were performed to compare crop parameter means. Analysis of covariance (ANCOVA) was performed for soil variables. This was done since significant ($p \leq 0.05$) differences in multiple soil variables were present between plots before the treatments were applied. Standard deviation was used as an indicator of the variability for the soil and plant properties measured. Spearman correlations were used to determine if the soil properties measured correlated with the crop measurements. For Spearman correlations, only significant ($p \leq 0.05$) results are reported. STATISTICA software version 13 was used to conduct the statistical analyses (TIBCO, 2018).

### 4.3 Results

#### 4.3.1 Soil results

*Soil chemical properties at the mid-2020 soil sampling*

The treatment where micro-fine pellets were broadcast and placed in-row, had the highest $pH_{(KCl)}$ in the 0 – 5 cm depth at the mid-2020 soil sampling (Figure 4.3, Table 4.2). However, this value was not higher ($p \leq 0.05$) than the $pH_{(KCl)}$ values at the same depth of the other treatments that contained pellets, except for the treatment where pellets were placed in-row only. Since most of the treatments where micro-fine lime pellets were applied were over-

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limed, the highest increase in soil $pH_{(KCl)}$ does not indicate the most effective treatment in this trial. The treatments where pellets were broadcast only and where pellets were placed in-row and broadcast had higher ($p > 0.05$) $pH_{(KCl)}$ values in the 0 – 5 cm depth than all other treatments, with exception of the treatment where pellets were applied at a rate of 19% less than the recommended rate. The $pH_{(KCl)}$ of the no disturbance broadcast 88% and 95% CCE Class A lime treatments were higher ($p > 0.05$) in the 0 – 5 cm depth than those of the control and where pellets were placed in-row only. None of the $pH_{(KCl)}$ values of the other treatments differed in the 0 – 5 cm depth. In the 5 – 15 cm depth, the treatment where pellets were broadcast only had a higher $pH_{(KCl)}$ than the control, all the 88% CCE Class A lime containing treatments and where 95% CCE Class A lime was broadcast. The $pH_{(KCl)}$ of the treatment where micro-fine lime pellets were broadcast only was, however, similar ($p > 0.05$) to those of the pellet treatments where 19% less than the recommended rate was applied or where pellets were applied both in-row and broadcast in the 5 – 15 cm depth.

**Table 4.2.** Results of mixed model analysis of variance (ANOVA) for soil samples taken in mid-2020 for $pH_{(KCl)}$, acid saturation (%), Ca (mg $kg^{-1}$) and effective cation exchange capacity (ECEC) (cmolc $kg^{-1}$).

| **Variable** | **F Statistic** | ***p* value** |
|---|---|---|
| **$pH_{(KCl)}$** | | |
| Depth | 17.96 | <0.001 |
| Treatment | 10.98 | <0.001 |
| Depth x Treatment | 1.01 | 0.457 |
| **Acid Saturation (%)** | | |
| Depth | 4.57 | 0.011 |
| Treatment | 4.80 | <0.001 |
| Depth x Treatment | 0.65 | 0.846 |
| **Ca (mg $kg^{-1}$)** | | |
| Depth | 121.43 | <0.001 |
| Treatment | 4.94 | <0.001 |
| Depth x Treatment | 1.57 | 0.087 |
| **ECEC (cmolc $kg^{-1}$)** | | |
| Depth | 102.90 | <0.001 |
| Treatment | 3.07 | <0.001 |
| Depth x Treatment | 1.06 | 0.398 |

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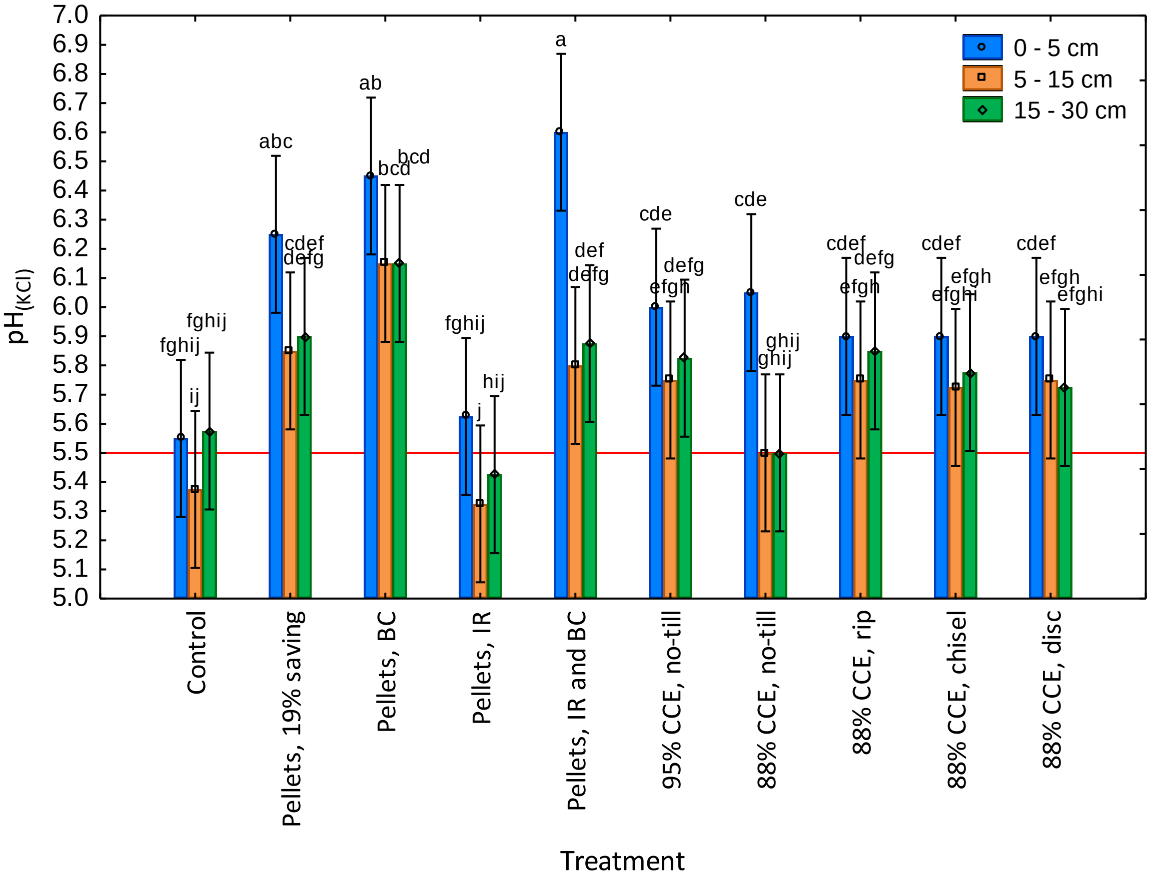


**Figure 4.3.** The $pH_{(KCl)}$ values for all three depths at the mid-2020 soil sampling. The red line indicates the target soil $pH_{(KCl)}$. No common superscript letter indicates a significant ($p \leq 0.05$) difference. BC = broadcast and IR = in-row.

The treatments that still had some exchangeable acidity, therefore also acid saturation, in at least one of the depths of sampling were the control, the no tillage, rip and disc plough treatments, the 95% CCE Class A lime with no tillage, as well as where pellets were applied in-row only (Figure 4.4, Table 4.2). The control treatment had the highest exchangeable acidity in all three depths respectively at the mid-2020 soil sampling. The second highest exchangeable acidity, for all three depths, were found where micro-fine lime pellets were applied in-row only. The exchangeable acidity, for each respective depth, were similar ($p \leq 0.05$) between the control and where micro-fine lime pellets were applied in-row only. All of the lime pellet treatments, except where pellets were applied in-row only, and the treatment where the chisel plough was used, had no exchangeable acidity in any of three layers of sampling. The 95% CCE Class A broadcast and the disc plough treatments had exchangeable acidity only in the 5 – 15 cm depth. The 5 – 15 cm depth had the highest mean for exchangeable acidity of the three layers of sampling.

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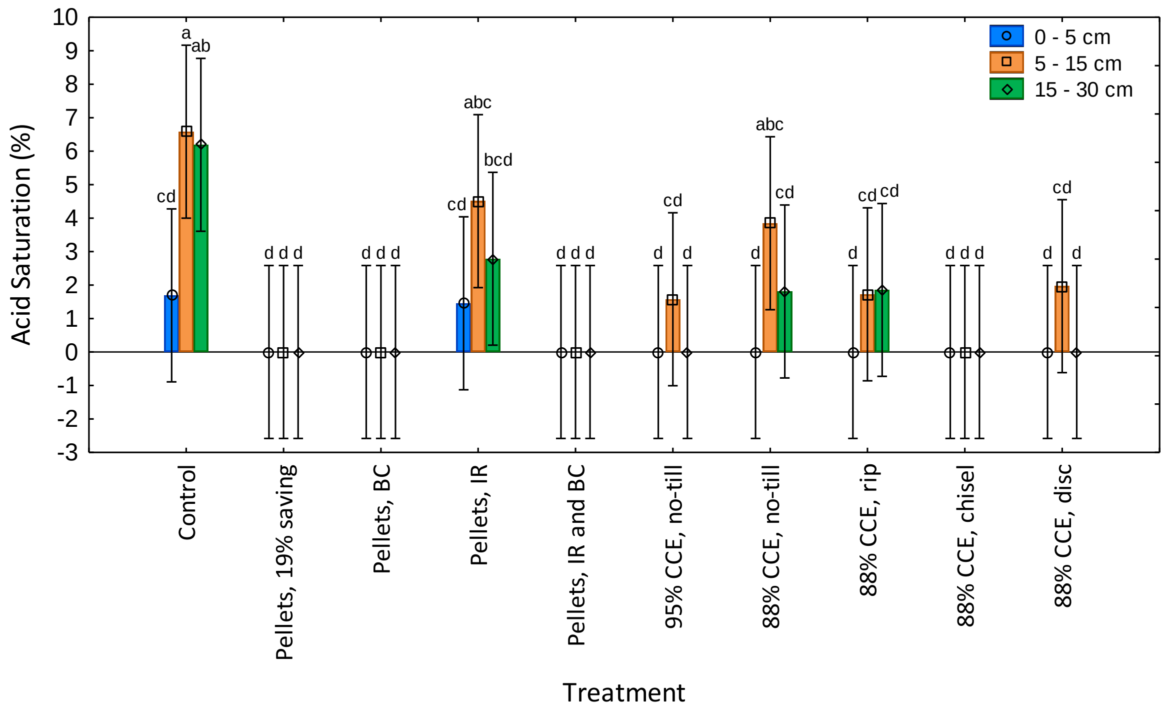


**Figure 4.4.** Acid saturation percentages of all treatments, per depth, at the mid-2020 soil sampling. No common superscript letter indicates a significant (p ≤ 0.05) difference. BC = broadcast and IR = in-row.

The treatment where micro-fine lime pellets were applied in-row and broadcast had the highest Ca contents in the 0 – 5 cm depth at the mid-2020 soil sampling, however it was similar ($p \leq 0.05$) to the treatment where pellets were broadcast only (Figure 4.5, Table 4.2). The Ca contents in the 0 – 5 cm depth of both these treatments were higher ($p > 0.05$) than all other treatments, except for the 95% CCE Class A lime broadcast treatment and the treatment where micro-fine lime pellets were broadcast only, which was similar ($p \leq 0.05$). The Ca contents at the mid-2020 sampling in the 5 – 15 cm depth were similar ($p \leq 0.05$) between most treatments, with the exception of the treatments where a chisel plough was used and where pellets were broadcast only, having higher ($p \leq 0.05$) Ca contents than the control treatment. At the mid-2020 soil sampling, the Ca contents in the 15 – 30 cm depth were similar ($p \leq 0.05$) between all treatments.

The ECEC of the treatment where micro-fine lime pellets were applied in-row as well as broadcast had the highest ECEC in the 0 – 5 cm depth and was higher ($p > 0.05$) than all other treatments, except for where pellets were broadcast only (Figure 4.6, Table 4.2). The treatment where micro-fine lime pellets were broadcast only was similar ($p > 0.05$) to the treatment where 95% CCE micro-fine lime was applied with no tillage and to the treatment

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where a chisel plough was used. None of the treatments where 88% CCE Class A lime was applied differed ($p > 0.05$) in ECEC values in the 0 – 5 cm depth.

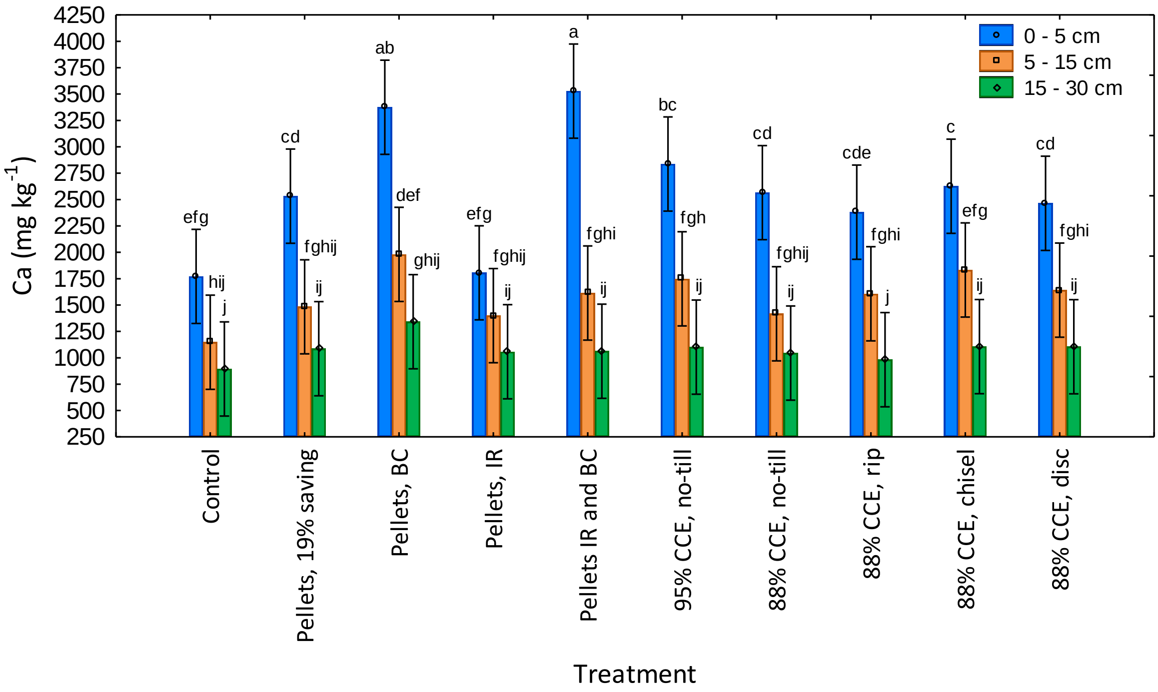


**Figure 4.5.** The Ca contents of all three depths at the mid-2020 sampling. No common superscript letter indicates a significant ($p \leq 0.05$) difference. BC = broadcast and IR = in-row.

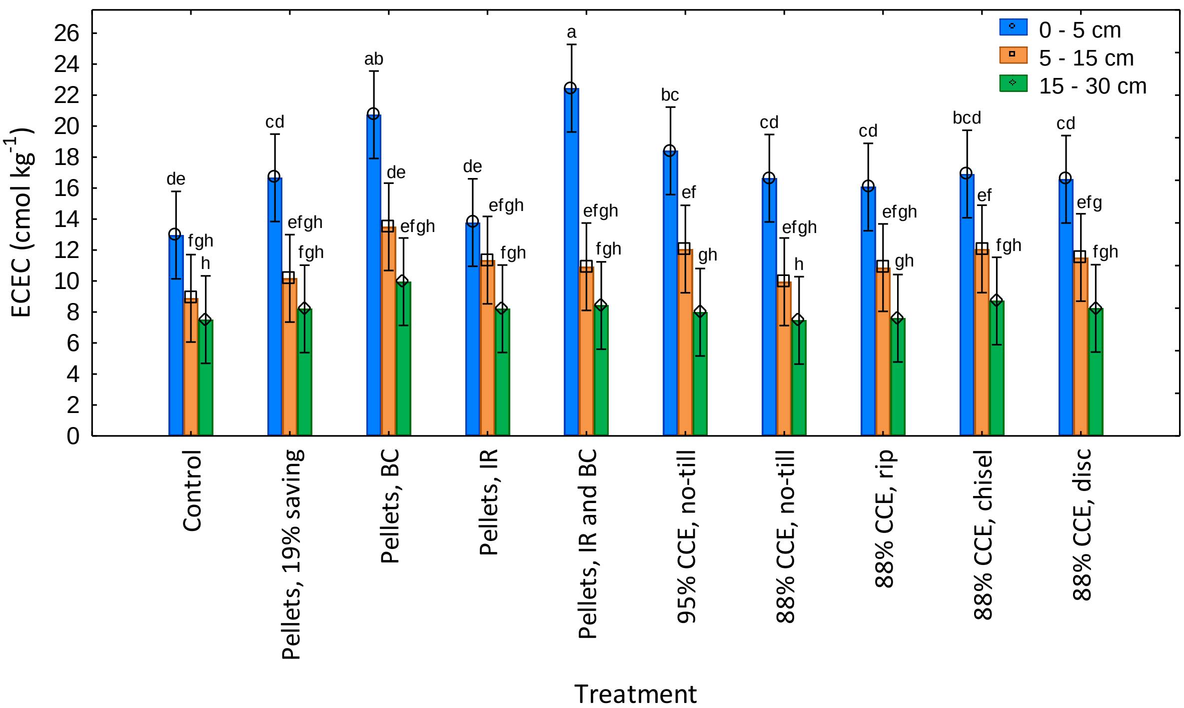


**Figure 4.6.** Effective cation exchange capacity (ECEC) of each treatment for all three depths sampled at the mid-2020 sampling. No common superscript letter indicates a significant ($p \leq 0.05$) difference. BC = broadcast and IR = in-row.

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*Changes between first and mid-2020 soil samples:*

The difference between the first samples taken (prior to planting in 2019) and the samples taken mid-2020 in values of $pH_{(KCl)}$, exchangeable acidity, acid saturation percentage, as well as the Ca and Mg contents for each treatment was calculated to compare the changes in soil chemical attributes over time.

All of the pelletised lime treatments, except where 40 kg $ha^{-1}$ was applied in-row only, and where 88% CCE Class A lime was applied with no tillage had higher ($p \leq 0.05$) changes in $pH_{(KCl)}$ than all other treatments (Figure 4.7, Table 4.3). The treatment where pellets were broadcast and applied in-row also had a bigger ($p \leq 0.05$) change in $pH_{(KCl)}$ than the treatments where rip and disc ploughs were used. The treatment where micro-fine lime pellets were applied only within crop rows was the only treatment that contained a liming material where the soil $pH_{(KCl)}$ decreased from the first to mid-2020 soil samplings. The only other treatment that showed a decrease in soil $pH_{(KCl)}$ was the control. This is to be expected, as no liming material was applied in the control treatment and the combination of natural acidification and the acidifying effect of the nitrogen fertiliser applications are expected to increase soil acidity.

**Table 4.3.** Results of mixed model analysis of variance (ANOVA) for the changes between the first soil samples taken and the soil samples taken in mid-2020.

| Variable | F Statistic | *p* value |
|---|---|---|
| **Change in $pH_{(KCl)}$** | | |
| Depth | 4.26 | 0.018 |
| Treatment | 14.13 | <0.001 |
| Depth x Treatment | 1.37 | 0.165 |
| **Change in Ca (mg $kg^{-1}$)** | | |
| Depth | 58.18 | <0.001 |
| Treatment | 4.65 | <0.001 |
| Depth x Treatment | 1.29 | 0.210 |

The treatment where micro-fine lime pellets were broadcast as well as applied in-row resulted in the greatest change in Ca content in the 0 – 5 cm soil depth (Figure 4.8, Table 4.3). The changes in Ca were similar ($p > 0.05$) between the no-tillage treatments, all three tillage treatments and where pellets were applied at 19% below the recommended rate. The control treatment had a similar change in Ca content ($p > 0.05$) to the treatments where pellets were applied within crop rows only and where rip and chisel ploughs were used. The change in Ca contents of the treatment where micro-fine lime pellets were applied in-row only differed (*p*

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≤ 0.05) from all other treatments, except the control, and also had the lowest change in Ca content of all treatments.

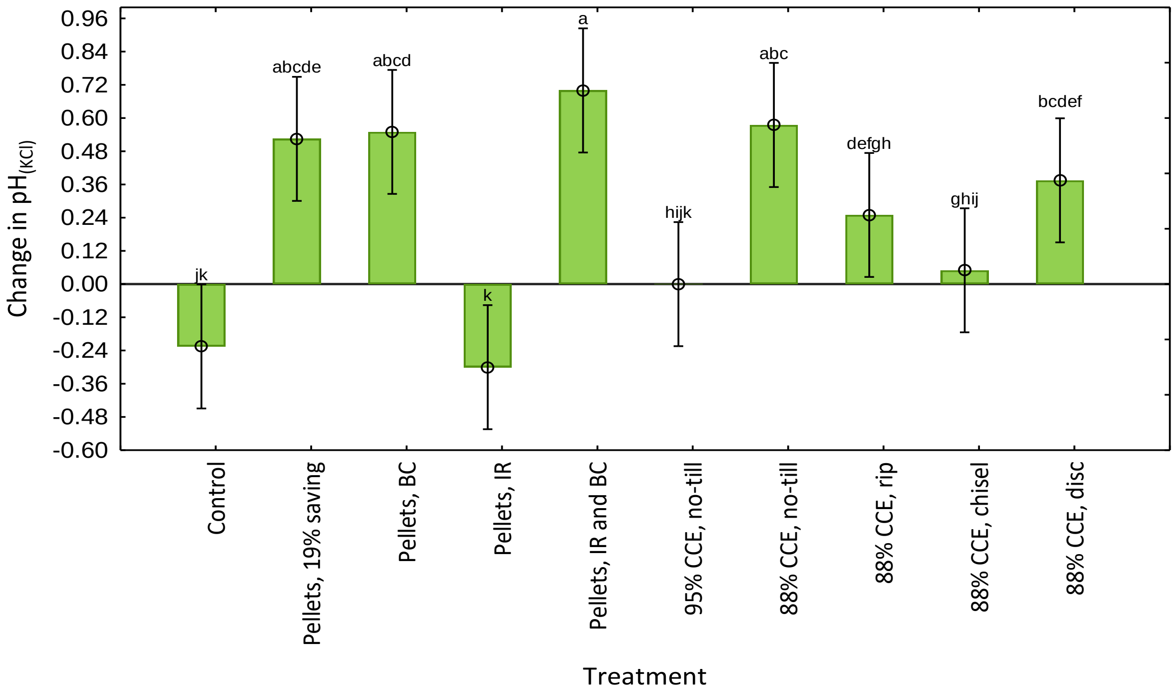


**Figure 4.7.** The change in $pH_{(KCl)}$ of the 0 – 5 cm depth layer between the mid-2020 soil sampling (taken in June of 2020) and the first soil sampling (taken prior to the application of treatments and crop establishment in March of 2019). No common superscript letter indicates a significant ($p \leq 0.05$) difference. BC = broadcast and IR = in-row.

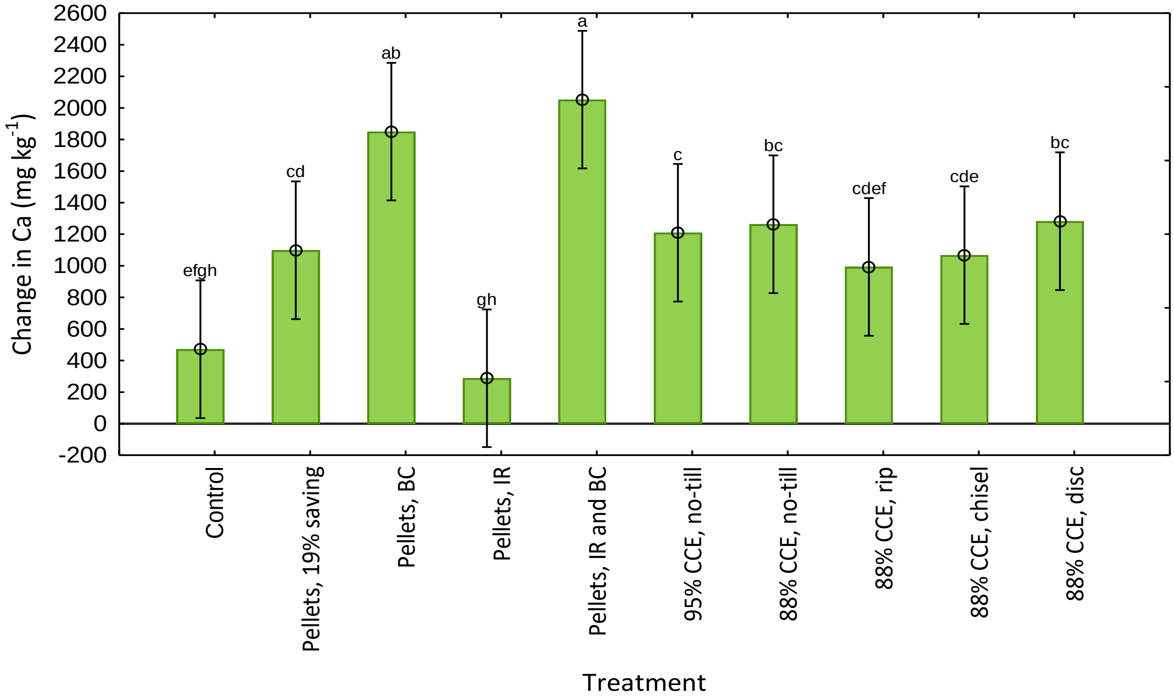


**Figure 4.8.** The change in Ca (mg $kg^{-1}$) of the 0 – 5 cm depth increment between the mid-2020 soil sampling (taken in June of 2020) and the first soil sampling (taken prior to the application of treatments and crop establishment in March of 2019). No common superscript letter indicates a significant ($p \leq$ 0.05) difference. BC = broadcast and IR = in-row.

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The change in Mg contents between the first and mid-2020 soil samplings were similar ($p > 0.05$) between all treatments (results not shown).

*Soil chemical properties in-row compared to between crop rows*

For the treatments where lime was applied at different rates in-row and as a surface-application, the soil chemical properties of the soil samples taken after harvest in 2019 were compared between these two locations of application.

Soil $pH_{(KCl)}$ values were similar ($p > 0.05$) between the in-row samples and the samples taken between crop rows for the control and the treatment where micro-fine lime pellets were applied in-row only (Figure 4.9). The soil $pH_{(KCl)}$ value of the samples taken between crop rows was higher ($p \leq 0.05$) than the value of the samples taken in-row for the treatments where micro-fine lime pellets were applied in-row and broadcast at the full recommended rate and where the broadcast rate was 19% lower than the recommended rate. The aforementioned two treatments also resulted in higher $pH_{(KCl)}$ values in both locations of sampling than the treatment where micro-fine lime pellets were applied in-row only.

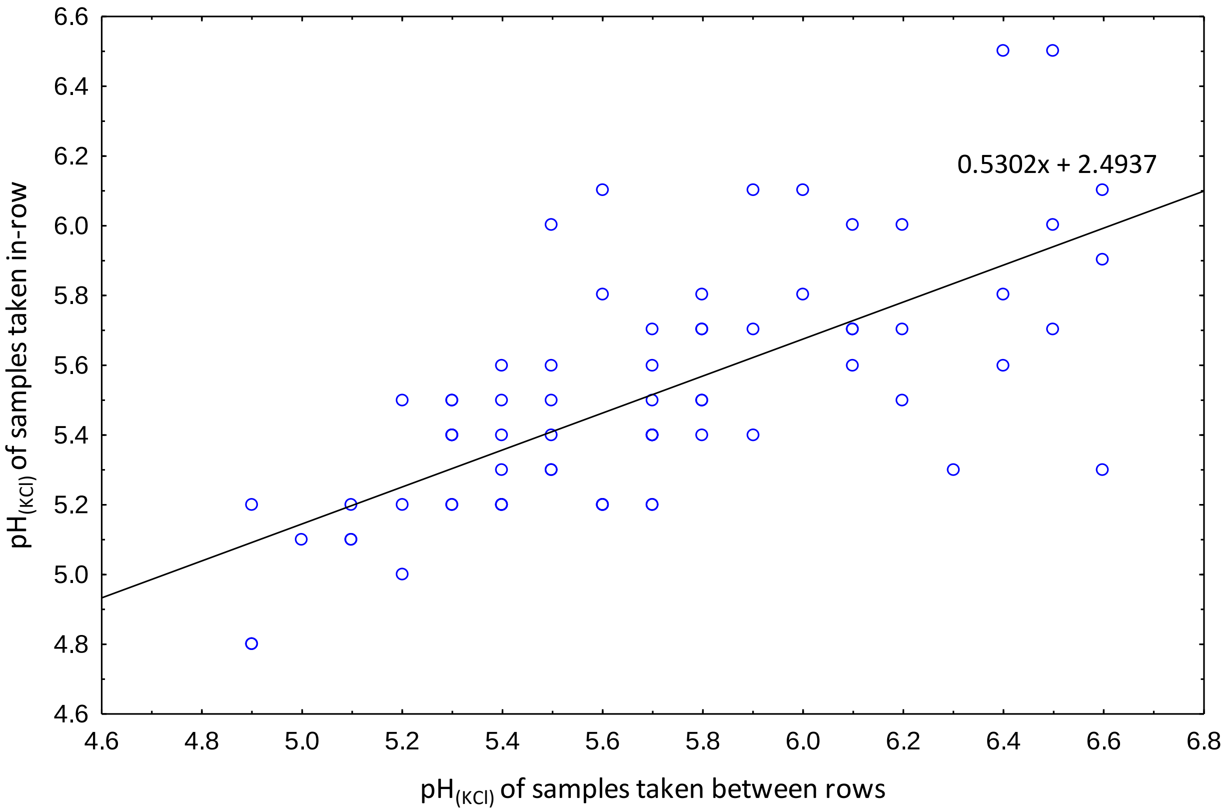


**Figure 4.9.** Correlation between soil $pH_{(KCl)}$ values of soil samples taken in-row and soil samples taken between crop rows ($p$ value = 0.009; $r^2 = 0.273$).

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The Ca contents of the samples taken between crop rows were higher ($p \leq 0.05$) than the Ca contents in-row where pellets were applied in-row and broadcast in the 0 – 5 cm soil depth (Figure 4.10). Of the samples taken between crop rows, the treatment where micro-fine lime pellets were applied in-row and broadcast had higher ($p \leq 0.05$) Ca contents than where pellets were applied in-row only. In the 5 – 15 and 15 – 30 cm depth layers, all treatments had similar ($p > 0.05$) Ca contents between the in-row samples and the samples taken between crop rows (results not shown). None of the Ca contents, for both locations of sampling, differed ($p > 0.05$) from one another in the 5 – 15 or 15 – 30 cm depth layers.

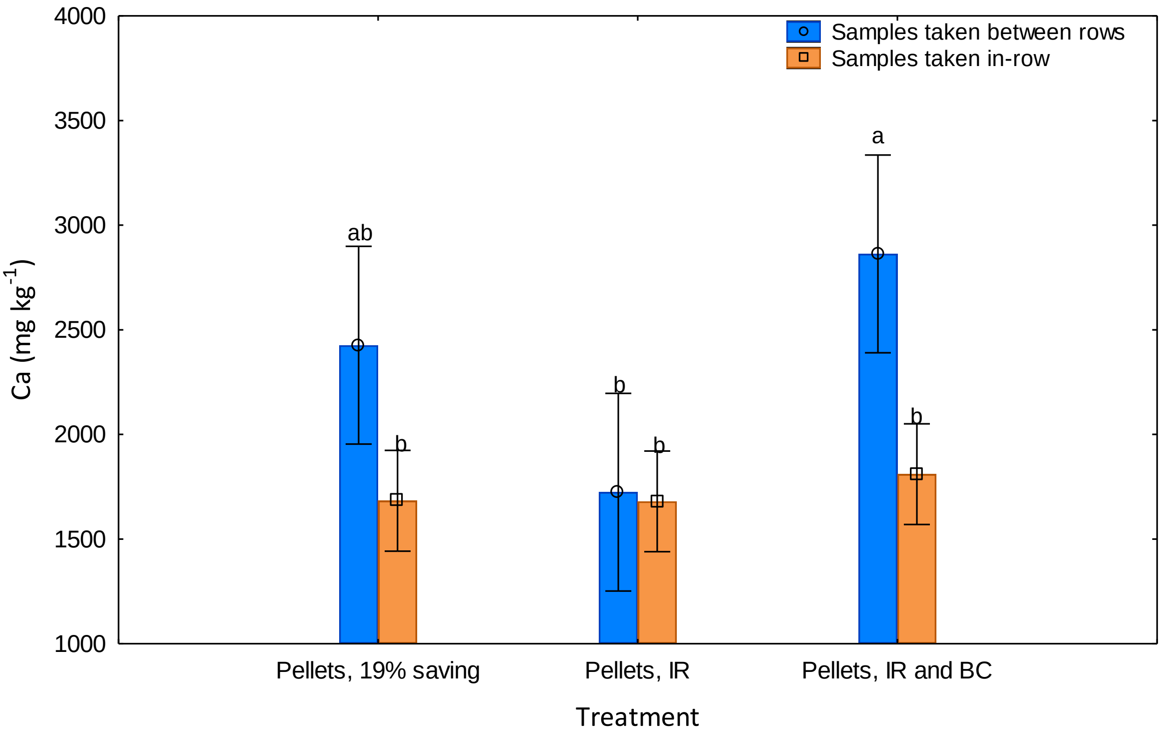


**Figure 4.10.** Comparison between soil Ca (mg kg$^{-1}$) contents in the 0 – 5 cm depth of soil samples taken in-row and soil samples taken between crop rows. No common superscript letter indicates a significant ($p \leq 0.05$) difference. BC = broadcast and IR = in-row.

### 4.3.2 Crop results

*Canola*

Results of repeated measures ANOVA for leaf area index and aboveground biomass (kg ha$^{-1}$) and results of one-way ANOVA for plant population (plants m$^{-2}$), seed yield (kg ha$^{-1}$), number of side-branches per plant, number of seeds per pod, thousand seed weight (g), oil content (%), oil yield (ton ha$^{-1}$) and harvest index for canola shown in Table 4.4.

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**Table 4.4.** Results of various one-way and repeated measure analysis of variance (ANOVA) analyses done on the various variables measured for canola.

| Variable | F Statistic | *p* value |
|---|---|---|
| **Plant population (plants m$^{-2}$)** | 1.43 | 0.22 |
| **LAI** | | |
| Treatment | 1.98 | 0.08 |
| DAE | 40.79 | 0.00 |
| Treatment x DAE | 1.93 | 0.03 |
| **Aboveground biomass (kg ha$^{-1}$)** | | |
| Treatment | 2.80 | 0.02 |
| DAE | 58.00 | 0.00 |
| Treatment x DAE | 1.02 | 0.46 |
| **Seed yield (ton ha$^{-1}$)** | 0.49 | 0.87 |
| **Number of side-branches per plant** | 0.65 | 0.74 |
| **Number of seeds per pod** | 0.81 | 0.61 |
| **Thousand seed weight (g)** | 0.28 | 0.97 |
| **Oil content (%)** | 2.36 | 0.04 |
| **Oil yield (ton ha$^{-1}$)** | 0.33 | 0.96 |
| **Harvest index** | 1.04 | 0.43 |

*In-season measurements*

For canola, the plant populations were similar ($p > 0.05$) between all treatments (results not shown). The mean plant population was 36.1 ± 9.8 plants m$^{-2}$. Although canola LAI's at 30 and 60 DAE were similar ($p > 0.05$), treatment effects were detected at 90 DAE (Figure 4.11, Table 4.4). The LAI's of the treatments where a chisel plough was used or when pellets were applied at 19% lower than the recommended rate were higher ($p \leq 0.05$) than the control. When a ripper was used, the LAI at 90 DAE was similar to the highest LAI.

The aboveground biomass production of canola (2019) showed no differences (p > 0.05) at 30 or 60 DAE (results not shown). At 90 DAE, only the treatment where micro-fine lime pellets were applied at 19% below the recommended rate, produced more ($p \leq 0.05$) biomass than the control, but no more biomass was produced after 90 DAE (Figure 4.12, Table 4.4). Maximum biomass production was therefore reached for the pellet-treatment with 19% saving at 90 DAE, not the case for several other treatments. None of the other treatments responded in biomass production ($p > 0.05$) at 90 DAE. The canola root biomass values at 30 DAE were similar ($p > 0.05$) between treatments (results not shown). These overall high values in aboveground biomass at 90 and 150 DAE may be ascribed to the dying off of plants throughout the growing season and therefore the use of plant population in the biomass calculation led to an overestimation.

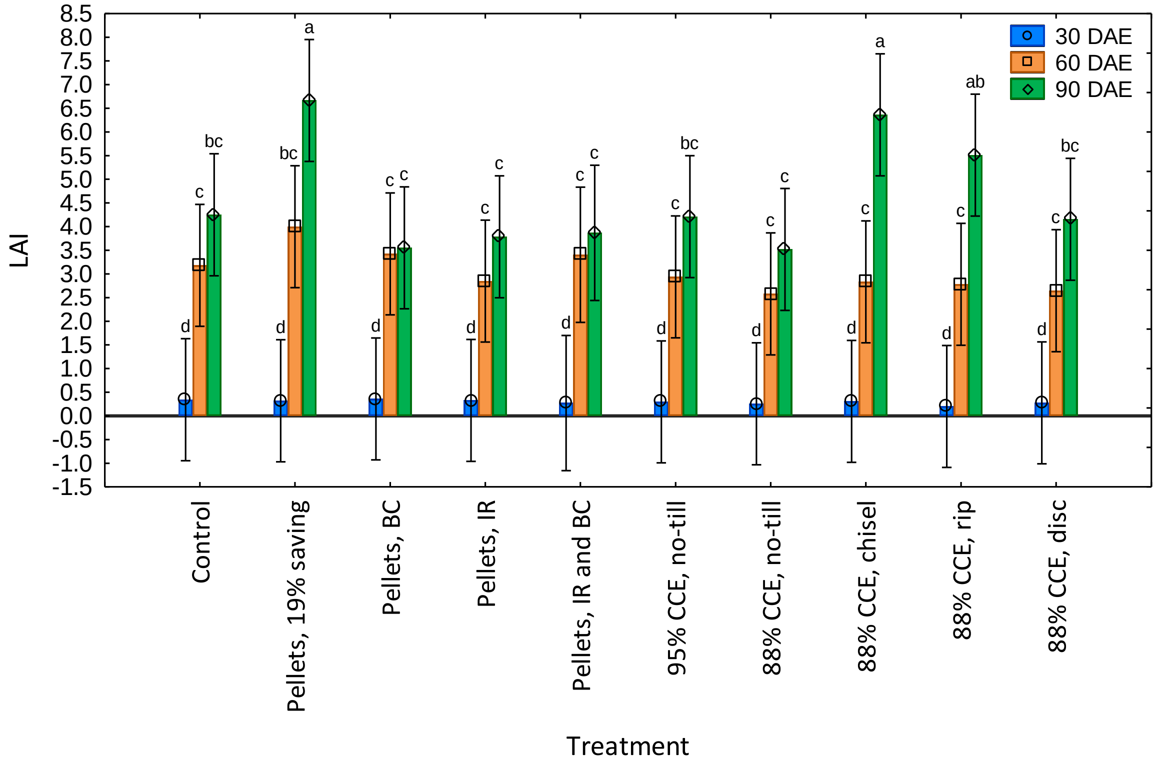


**Figure 4.11.** Leaf area index (LAI) of each lime treatment at 30, 60 and 90 DAE for canola (2019). No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row.

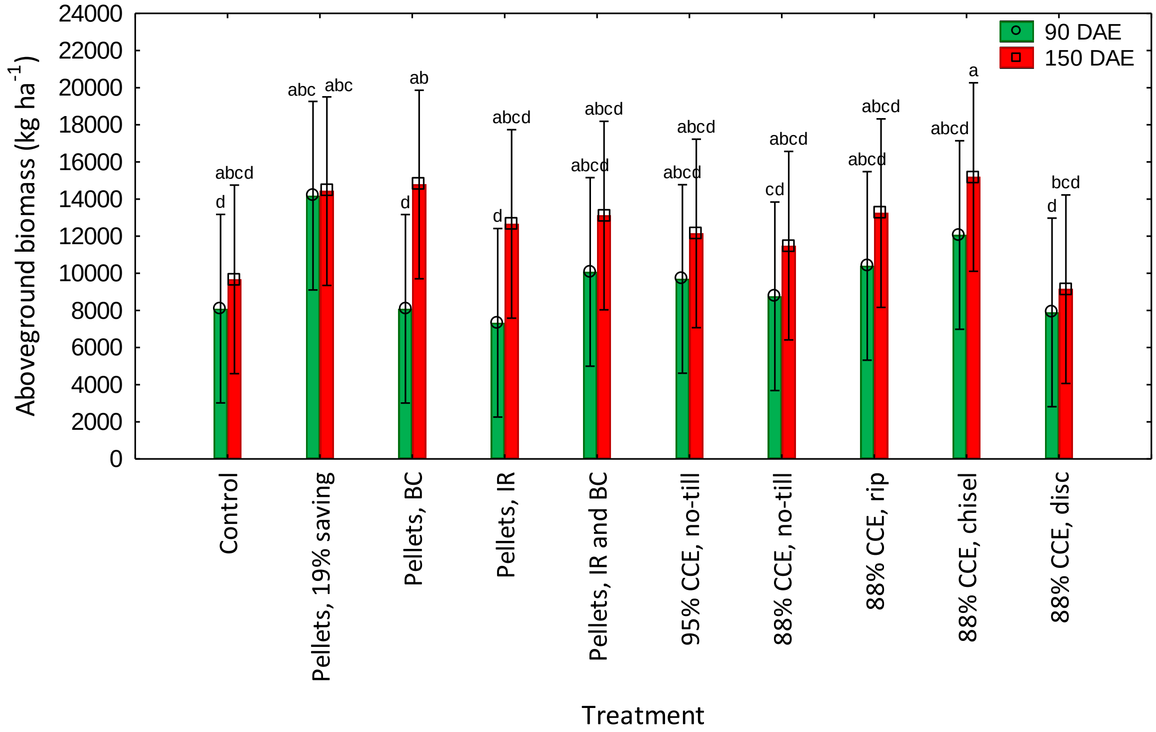


**Figure 4.12.** Aboveground biomass (kg ha$^{-1}$) for each treatment at 90 and 150 DAE of canola. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row.

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*Seed yield, yield components and seed quality*

No yield effect ($p > 0.05$) was found for canola (results not shown). The mean yield was 1.62 ± 0.27 t $ha^{-1}$. Neither number of side-branches per plant (11.48 ± 3.18), nor the number of seeds per pod (20.73 ± 2.05) showed a response to treatments (results not shown). All treatments also had similar ($p > 0.05$) harvest Indices (results not shown).

Oil content of the treatment where 88% CCE Class A lime was broadcast was higher ($p \leq 0.05$) than that of the treatments where micro-fine lime pellets were applied in-row only and where a disc plough was used (Figure 4.13, Table 4.4). Oil yield of all treatments were similar ($p > 0.05$), with the mean oil yield being 0.76 tons $ha^{-1}$ ± 0.13 (results not shown). No differences ($p > 0.05$) were found in thousand seed weight (3.42 g ± 0.14) between treatments (results not shown).

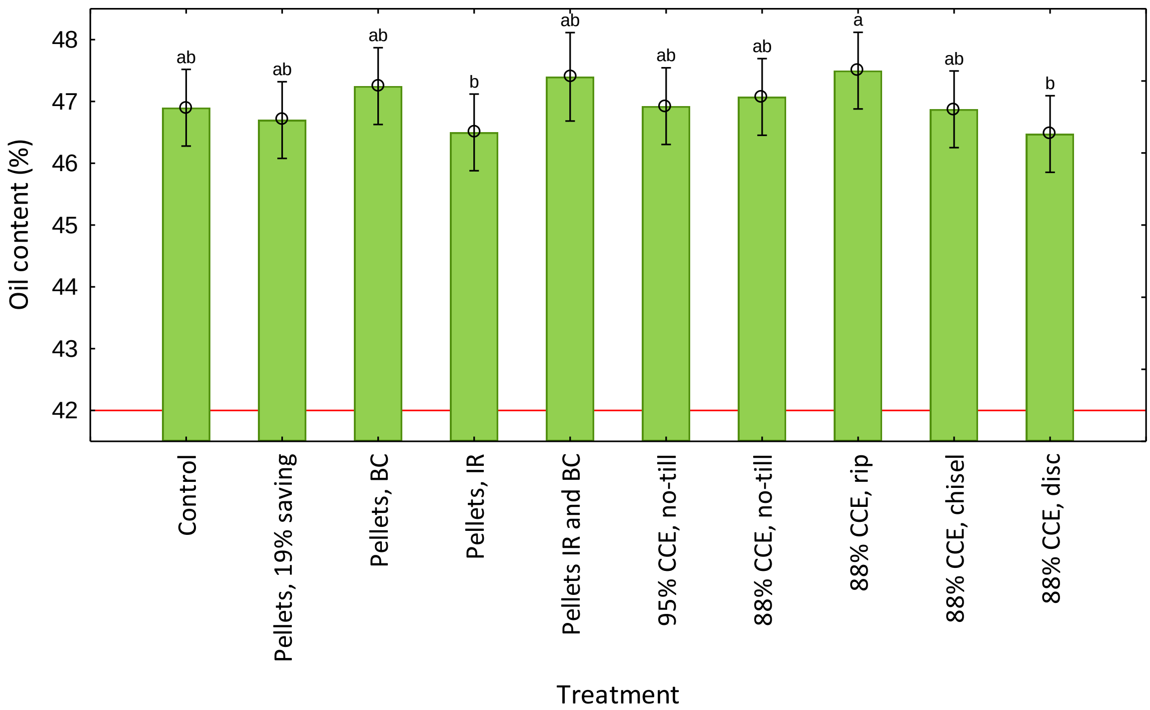


**Figure 4.13.** Canola oil content (%) per treatment. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row. The red line indicates the baseline set by the Australian Oilseeds Federation (2009).

*Wheat*

Results of repeated measures ANOVA for leaf area index and aboveground biomass (kg $ha^{-1}$) and results of one-way ANOVA for plant population (plants $m^{-2}$), grain yield (kg $ha^{-1}$), number of ear-bearing tillers, thousand kernel weight (g), dry protein content (%), wet gluten content (%), hectolitre mass (kg $hL^{-1}$) and harvest index for wheat are shown in Table 4.5.

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**Table 4.5.** Results of various one-way and repeated measure analysis of variances done on the various crop variables measured for wheat.

| Variable | F Statistic | *p* value |
|---|---|---|
| **Plant population (plants m$^{-2}$)** | 2.95 | 0.0141 |
| **LAI** | | |
| Treatment | 1.55 | 0.178 |
| DAE | 1.89 | 0.256 |
| Treatment x DAE | 0.79 | 0.631 |
| **Aboveground biomass (kg ha$^{-1}$)** | | |
| Treatment | 2.54 | 0.030 |
| DAE | 21.70 | 0.002 |
| Treatment x DAE | 1.37 | 0.187 |
| **Grain yield (ton ha$^{-1}$)** | 1.40 | 0.235 |
| **Number of ear-bearing tillers** | 2.02 | 0.071 |
| **Thousand kernel weight (g)** | 1.27 | 0.298 |
| **Dry protein content (%)** | 1.14 | 0.359 |
| **Wet gluten content (%)** | 1.06 | 0.417 |
| **Hectolitre mass (kg hL$^{-1}$)** | 0.56 | 0.810 |
| **Harvest index** | 0.47 | 0.878 |

*In-season measurements*

For wheat, plant populations were the highest when a disc plough was used and when micro-fine lime pellets were placed in-row and/or broadcast (Figure 4.14, Table 4.5). The lowest plant population was obtained after a rip plough was used. The treatment where a rip plough was used had a lower ($p \leq 0.05$) plant population than the other tillage treatments and all of the treatments where pellets were applied, except for where pellets were applied at 19% less than the recommended rate. The treatment where a rip plough was used did however not differ ($p > 0.05$) from the control or the no tillage treatments.

Aboveground biomass values between all treatments were similar ($p > 0.05$) at 60 and 90 DAE, respectively (results not shown). The mean aboveground biomass at 90 DAE was 14988.47 kg ha$^{-1}$ ± 4631.80. At 150 DAE, the control and where micro-fine pellets were applied in-row, had the lowest aboveground biomass values (Figure 4.15). The treatment where a disc plough was used, had the highest aboveground biomass at 150 DAE. The harvest indices of all treatments were also similar ($p > 0.05$), and the mean was 0.53 ± 0.08 (results not shown).

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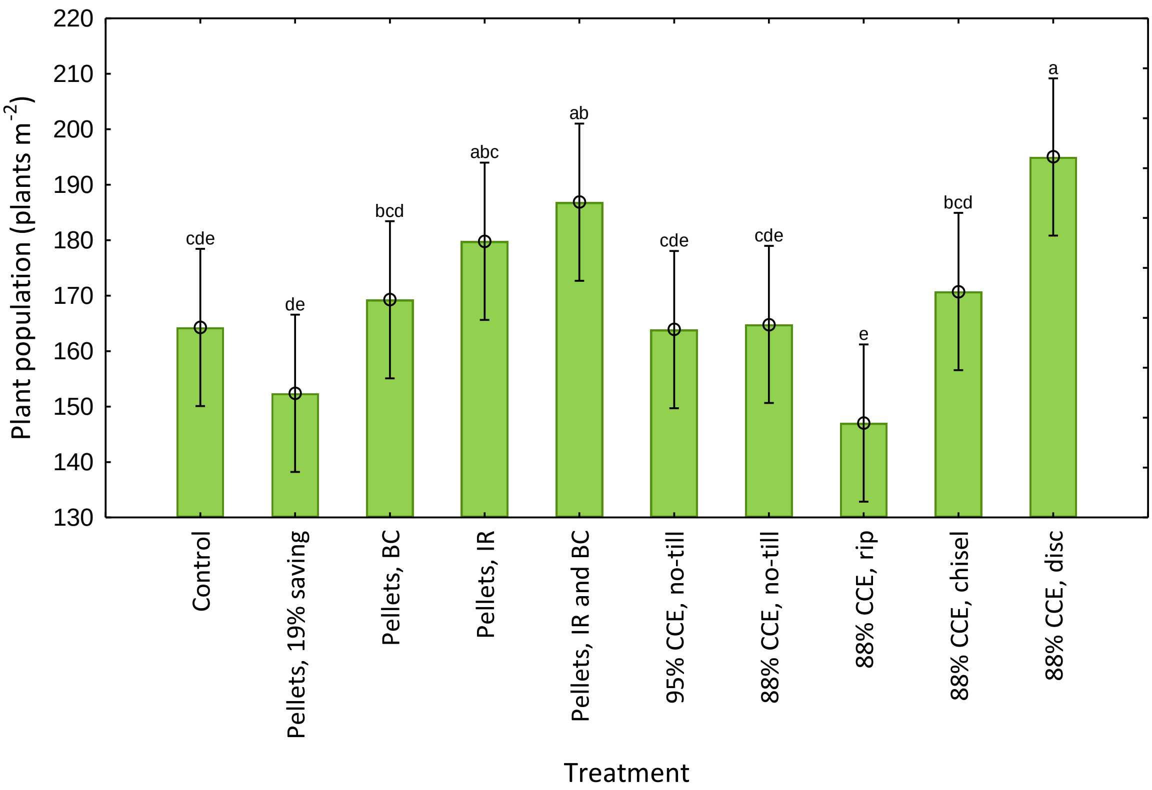


**Figure 4.14.** Wheat plant population for all treatments. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row.

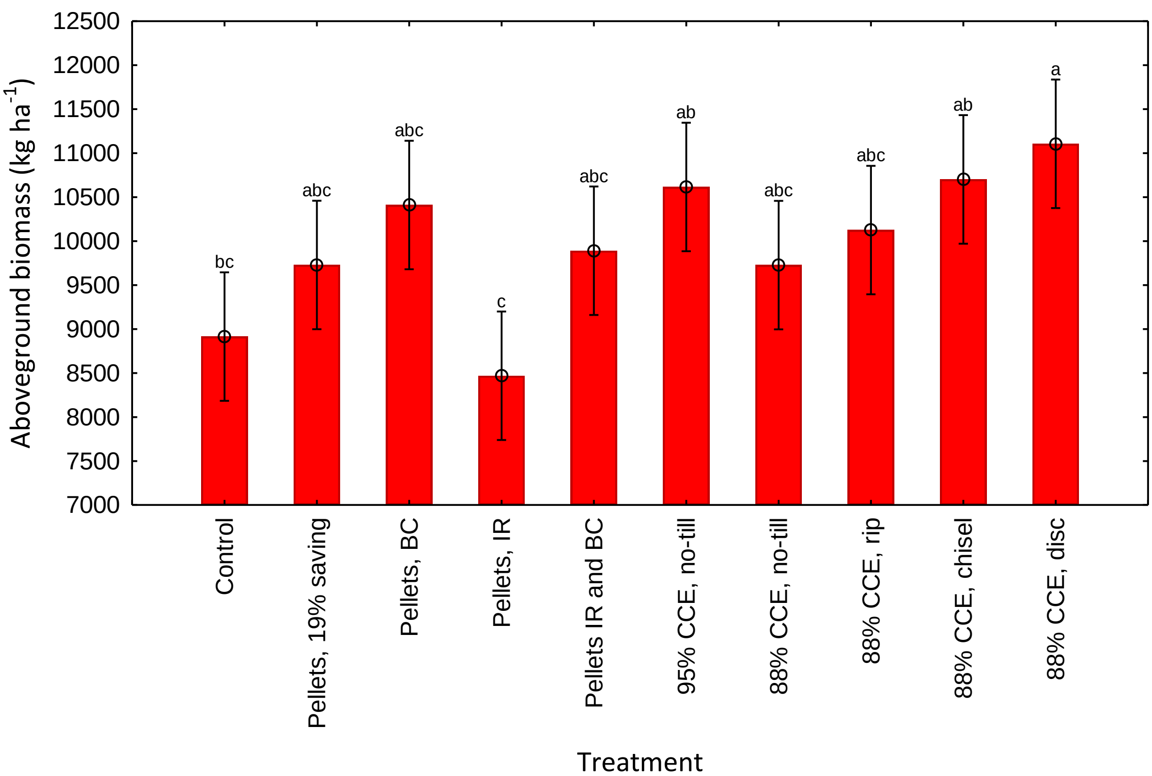


**Figure 4.15.** Wheat aboveground biomass values at 150 days after emergence (DAE) for all treatments. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row.

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*Wheat grain yield, yield components and quality*

Wheat grain yield was similar ($p > 0.05$) between all treatments (results not shown). The mean yield was 5.19 t ha$^{-1}$ ± 0.75. No differences ($p > 0.05$) in number of ear-bearing tillers were found for wheat (results not shown). Thousand kernel weight was similar between all treatments (results not shown). The mean thousand kernel weight was 47.51 g ± 1.45.

No treatment effect was found for hectolitre mass (77.17 kg hL$^{-1}$ ± 0.93; results not shown). The treatment where a chisel plough was used had a higher ($p \leq 0.05$) protein content than the control (Figure 4.16, Table 4.5). Protein contents of all other treatments were similar ($p > 0.05$) to the control and the treatment where a chisel plough was used. The mean protein content was 12.65% ± 0.70. A chisel plough resulted in a higher ($p \leq 0.05$) gluten content than the control (Figure 4.17). The mean gluten content was 28.87% ± 1.84.

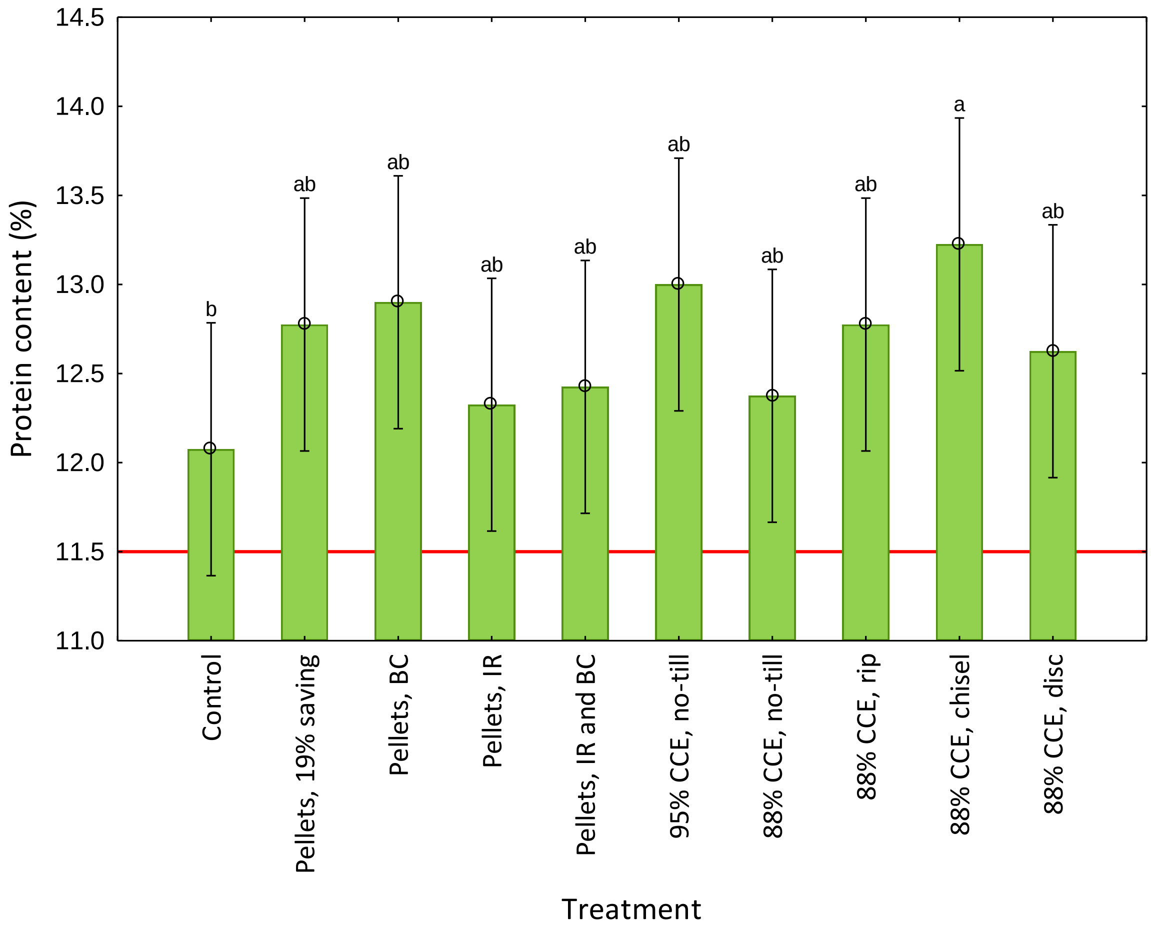


**Figure 4.16.** Wheat protein content (%) of each treatment. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row. The red line indicates the threshold value for B1 grading as specified by the ARC (2020).

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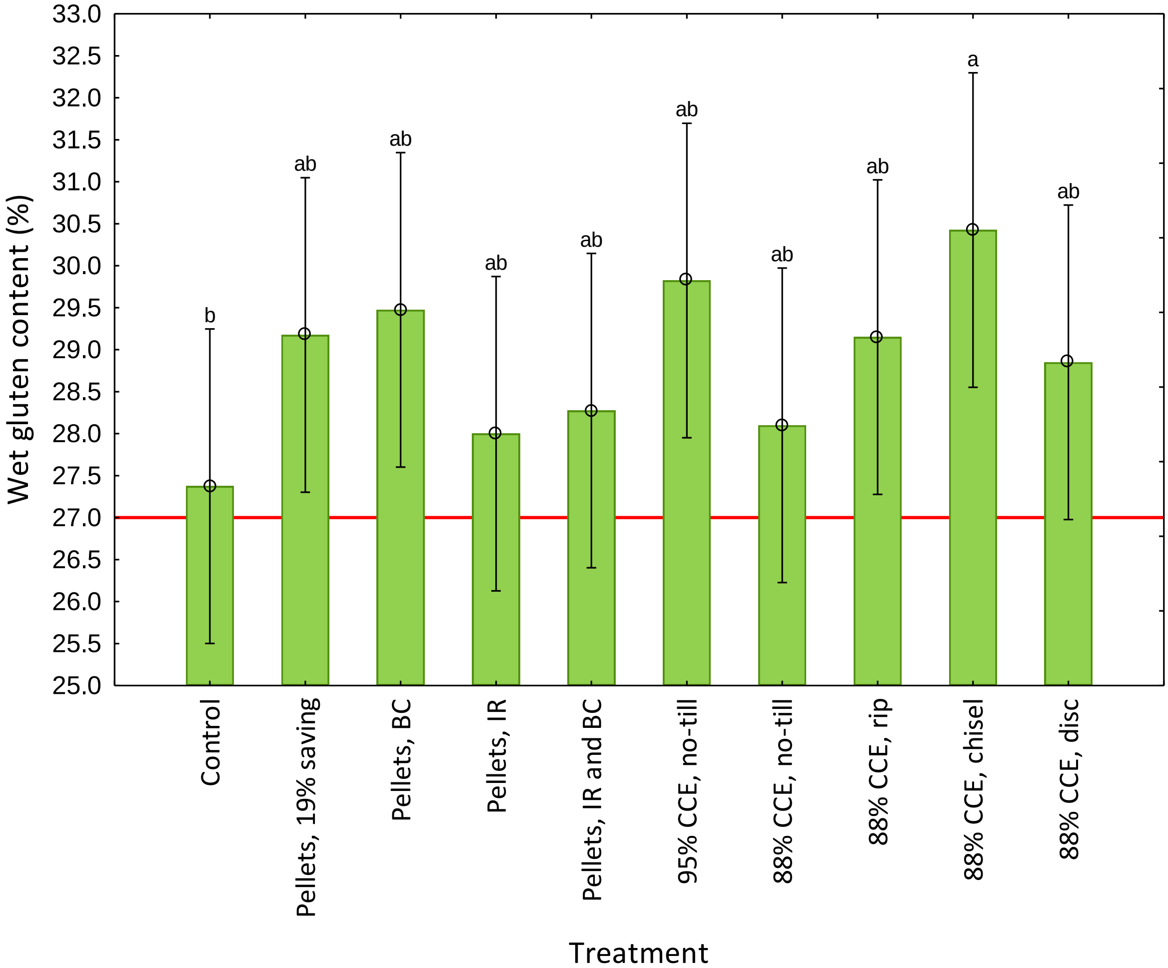


**Figure 4.17.** Wet gluten content of the wheat grain for each treatment. No common superscript letter indicates a significant ($p \leq 0.05$) difference. CCE = calcium carbonate equivalence; BC = broadcast; IR = in-row. The red line indicates the lower limit for B1 grading as specified by die ARC (2017).

### 4.3.3 Correlations between soil properties and crop measurements

No correlations ($p > 0.05$) were found in the 0 – 5 or 5 – 15 cm soil depths between the various soil properties and crop measurements. In the 15 – 30 cm soil depth, however, soil $pH_{(KCl)}$ correlated with the aboveground biomass ($p \leq 0.05$; Spearman $r^2 = 0.44$) of wheat at 150 DAE and with ECEC ($p \leq 0.05$; Spearman $r^2 = 0.50$) (Figure 4.18). Soil $pH_{(KCl)}$ in the 15 – 30 cm soil layer also correlated ($p \leq 0.05$; Spearman $r^2 = 0.39$) with wheat grain protein content (Figure 4.18).

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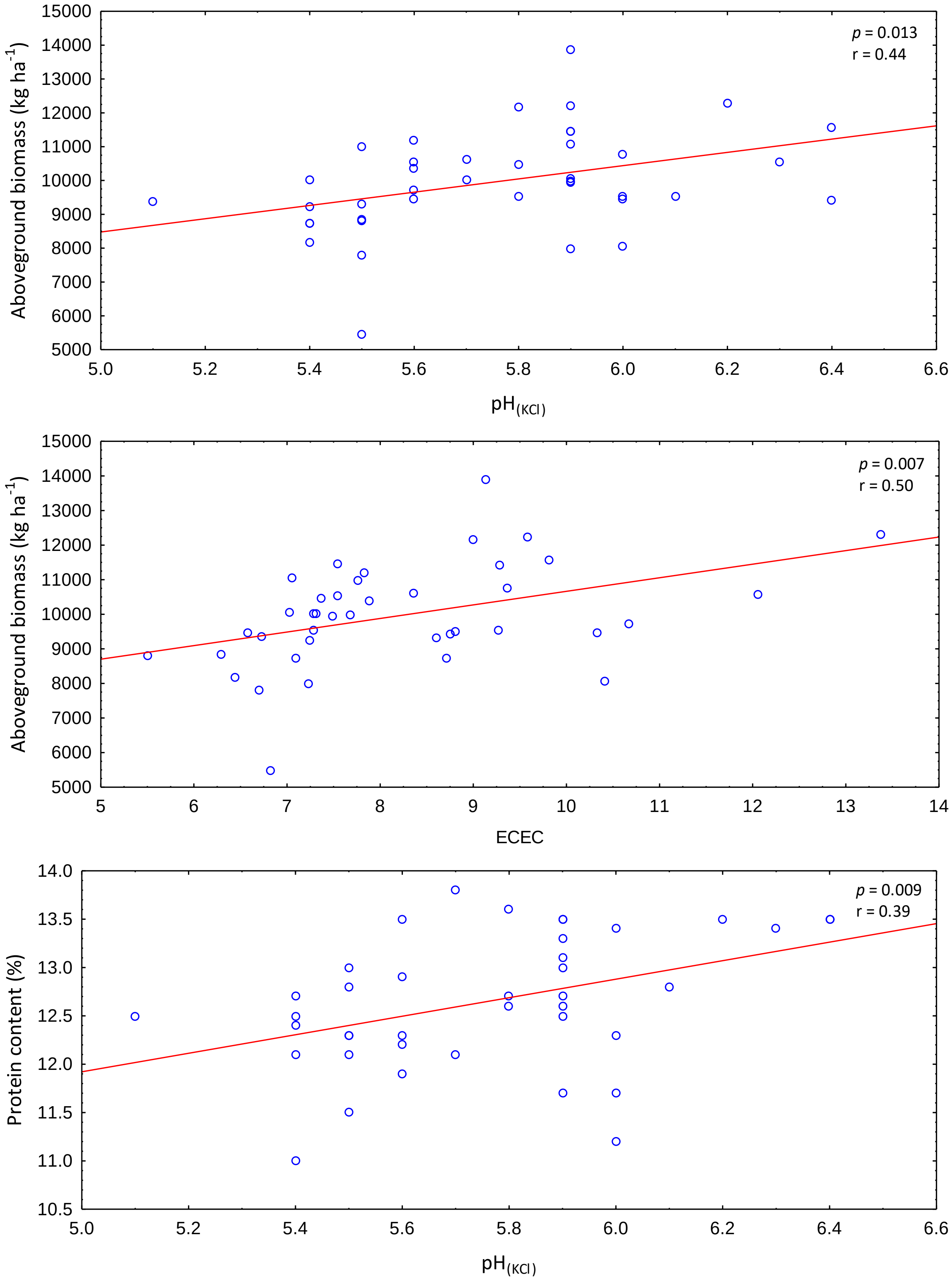


**Figure 4.18.** Spearman correlations in the 15 – 30 cm soil depth between soil $pH_{(KCl)}$ and aboveground biomass of wheat at 150 days after emergence (top), effective cation exchange capacity (ECEC) and aboveground biomass of wheat at 150 DAE (middle) and soil $pH_{(KCl)}$ and wheat grain protein content (bottom).

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## 4.4 Discussion

### 4.4.1 Soil results

The initial soil sampling to determine the lime requirement was taken representatively for the entire field and not for the trial site within the field (see Addendum C for initial soil analyses, prior to treatment application). Unfortunately, large variability within the field led to overestimation of lime requirement for the site. Over-liming that evident in some treatments where the mid-2020 $pH_{(KCl)}$ values were well above 6.0. Although the increase in $pH_{(KCl)}$ in some treatments may result in some nutrient deficiencies starting to develop in some crops, specifically Fe and Mn, even the over liming in some treatments could not neutralise all the free acidity found throughout the entire soil profile (Fernández and Hoeft, 2009; Foth, 1990). The importance of addressing subsoil acidity problems is supported by the positive correlation found between increasing soil $pH_{(KCl)}$ and ECEC in the 15 – 30 cm soil depth and increased aboveground biomass yield and protein content of wheat. The over-liming that was observed in the 0 – 5 cm soil depth of the treatments where micro-fine lime pellets were broadcast, may have detrimental effects in the future on crop performance and nutrient uptake. This severe difference in soil acidity between the top-and subsoil may restrict root development and lead to yield penalties over time (Caires *et al.*, 2008).

In general, the mid-2020 soil $pH_{(KCl)}$ values of all treatments ranged from 5.5 to 6.5 in the 0 – 5 cm depth layer, from 5.3 to 6.1 in the 5- 15 cm depth layer and from 5.4 to 6.1 in the 15 – 30 cm depth layer. The greatest difference in soil $pH_{(KCl)}$ between the 0 – 5 and 5 – 15 cm layers of the same soil was 0.8 units. This large disparity in soil $pH_{(KCl)}$ between soil layers is unsurprising, as broadcast limestone is known to react quickly with topsoil acidity, but is slow to address subsoil acidity (Caires *et al.*, 2008; Ernani *et al.*, 2004). The control, where no liming material was applied, showed a decrease in soil $pH_{(KCl)}$ in the 0 – 5 cm depth of 0.23 over the course of this trial. Soils acidify over time due to various factors including the leaching of basic cations and the parent material having low concentrations of basic cations, therefore this result is to be expected (Fageria and Baligar, 2008). The application of an 88% CCE class A lime with no tillage was just as effective at raising topsoil pH as the surface application of micro-fine lime pellets, both at the full rate of the lime requirement and at 19% below the recommended rate. Although the treatments where lime was physically incorporated had a smaller ($p \leq 0.05$) change in topsoil pH than the treatments where lime was physically incorporated, the physical disturbance of the soil did however result in more uniform soil pH

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values over all depth layers. None of the three depth layers differed ($p > 0.05$) between the three tillage treatments. This same trend was observed, yet to a lesser degree, in the Ca contents of the three depth layers, where the 5 – 15 and 15 – 30 cm layers of sampling of the treatment with disc plough tillage showed similar ($p > 0.05$) Ca contents. The Ca contents in all three layers for the treatment where micro-fine lime pellets were placed in-row only were similar ($p > 0.05$) to the control, where no lime was applied. This treatment was also the only treatment, along with the control, where exchangeable acidity remained in the topsoil at the end of the trial.

The small amount (40 kg $ha^{-1}$) of micro-fine lime pellets that were applied in-row was ineffective at raising soil $pH_{(KCl)}$. This is evident from the results that show that the treatment where micro-fine lime pellets was applied in-row only was the only treatment, apart from the control, where soil $pH_{(KCl)}$ decreased over the course of the trial. This result reflected in exchangeable acidity, where an application rate of 40 kg $ha^{-1}$ still had exchangeable acidity in the 0 – 5 cm soil layer in the mid-2020 sampling. These results contradict the information that some companies provide regarding the application of a small amount of micro-fine lime pellets supposedly having the same neutralisation effect on soil acidity as a large amount of Class A lime. The conclusion that the application of a small amount of micro-fine lime pellets is ineffective, was also reached where micro-fine lime pellets were evaluated in a field trial done with corn (Lentz *et al*., 2010). The $pH_{(KCl)}$ values between samples taken in-row and samples taken between crop rows of the treatment where micro-fine lime pellets were applied in-row only were also similar ($p > 0.05$). Thus, the application of micro-fine lime pellets at a rate of 40 kg $ha^{-1}$ in-row only is comparable to not applying limestone at all in terms of the effect thereof on raising soil $pH_{(KCl)}$ in these soil and climatic conditions. The higher ($p \leq 0.05$) change in $pH_{(KCl)}$ observed between crop rows compared to in-row in the treatments where pellets were applied in-row and broadcast, also indicates that the low amount of pellets applied in-row is not as effective as a broadcast lime application at raising soil $pH_{(KCl)}$. This trend was observed with the increase in Ca contents of the soil layers, where the broadcasting of micro-fine lime pellets was more effective at raising Ca contents of the soil than the in-row placement of small amounts of micro-fine lime pellets.

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The lack of meaningful differences between the first and mid-2020 soil samplings in the Mg contents in the soils was as expected since none of the liming materials included in this trial were dolomitic and therefore no application of Mg was done.

Furthermore, the changes in values of exchangeable acidity and acid saturation percentages were not meaningful. The plots where some of the treatments were to be applied had no acidity to neutralise, prior to the start of the trial. Therefore, the change in values for exchangeable acidity and acid saturation percentages was not meaningful due to both these variables not accommodating negative values.

### 4.4.2 Crop results

*Canola*

In general, canola plant populations ranged from 30 to 40 plants m$^{-2}$, which is slightly below the South African ideal for these climatic conditions (DAFF, 2016). All plant populations were however within the range given by the Grain Research and Development Centre for similar rainfall areas (GRDC, 2015). Canola plant populations were above the minimum threshold for profitability given by the Canola Council of Canada (2020). These similar plant populations could explain the lack of variability in the variables that were noted, such as numbers of side-branches per plant and seeds per pod, since similar plant populations are expected to show similar branching patterns.

The highest LAI for canola was observed at 90 DAE, with two treatments having LAIs greater than 6. Most treatments did however result in LAI's at 90 DAE that were near 4, which is the most optimal for canola (Canola Council of Canada, 2020). The lack of differences between treatments in various variables and at different growth stages in the canola crop may be ascribed to canola's ability compensate remarkably well (McCaffery *et al*., 2009; Swanepoel *et al.*, 2019). This could also account for the differences observed in canola at the later growing stages, where LAIs and biomasses between treatments differed throughout the growing season ($p \leq 0.05$), but the final yields were similar ($p > 0.05$). As for the seed yields, the harvest indices were similar ($p > 0.05$) between all treatments. This result may be ascribed to the irregular spread of rainfall, as well as the overall low amount of rainfall that the region received in 2019.

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Seed oil contents ranged from 46.48 to 47.50%, which is greatly above the minimum threshold of 42% given by the Australian Oilseeds Federation (2009). All treatments had a thousand seed weight in the small (3.3-3.9 g) to medium (4.0-4.9 g) seed size range for canola seed (Australian Oilseeds Federation, 2019).

*Wheat*

Wheat plant populations ranged from 147 to 195 plants m$^{-2}$, which is ideal for the region (ARC, 2017). Plant populations for nearly all treatments were near the recommended values, with only the treatment where pellets were applied at 19% below the recommended rate and the treatment a rip plough was used being below the recommended range for plant populations (ARC, 2017).

The lack of meaning differences between treatment LAI's may be ascribed to the even rainfall distribution throughout the growing season and treatment differences may potentially be more prominent in drier years, where the crop does not have a sufficient supply of rainfall throughout the growing season. The overall high values in aboveground biomass may be the result of plant population being used to calculate aboveground biomass and the dying off of plants throughout the growing season therefore led to an overestimation of aboveground biomass.

Wheat yields for all treatments were greatly above the mean of the previous four years of the region (2016-2019), with the lowest yielding treatment (where micro-fine lime pellets were applied in-row only) having yielded 4.4 t ha$^{-1}$, which is over 1.3 t ha$^{-1}$ higher than the mean of the previous four years of the region (ARC, 2020). The highest yielding treatments (the treatments where rip and chisel ploughs were used) yielded over 5.6 t ha$^{-1}$, which is over 2.5 t ha$^{-1}$ more than the mean of the past four years of the region (ARC, 2020). The mean harvest index was 0.53 ± 0.08, which is high compared to results of wheat in other Mediterranean climatic areas and compared to various cultivars (Dai *et al.*, 2016; Kobata *et al.*, 2018)

For wheat, the thousand seed weight of all treatments were in the upper range given by the ARC (2017). The protein contents of all treatments were high enough (> 11.5%) to be graded as B1, also referred to as Grade 1 (ARC, 2020). Wet gluten contents of all treatments were within the required ranges (27-33%) for classification as Grade 1/B1 (ARC, 2017). The hectolitre masses of all treatments also qualified for Grade 1/B1 grading (ARC, 2017).

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### 4.4.3 Correlations between soil properties and crop measurements

No positive or negative correlation ($p > 0.05$) were found between soil properties and canola measurements. It has been observed that the positive response of canola to the liming of soils may be ascribed to the reduction in Al and Mn, rather than responding to the liming material directly (Scott *et al*., 2003). Thus, the lack of correlations between soil properties and canola measurements may be ascribed to the low amounts of acidity, therefore also low amounts of free Al and Mn, in the soil. The lack of correlations between soil properties and canola, which was the crop in the same year that the liming materials were applied, may further be ascribed to the slow reaction of limestone to neutralise soil acidity, especially in the subsoil (Fageria and Nascente 2014; Liu and Hue 2001).

Both the aboveground biomass at 150 DAE and wheat grain protein content correlated positively ($p \leq 0.05$) with increased soil $pH_{(KCl)}$ in the 15 – 30 cm soil depth. This increase in quality of wheat crops corresponds with Caires *et al*. (2006), where surface application of limestone led to improved quality of wheat. The comparable wheat grain yields between most treatments supports previous findings where liming in a no-tillage system did not lead to a significant increase in wheat grain yield (Godsey *et al*., 2007). The lack of response in wheat yield, following surface application of limestone, was ascribed to a combination of the liming material not neutralising soil acidity in the rooting zone shortly after application and the overall low levels of acidity in the soil of the trial site. The aboveground biomass of wheat also correlated ($p \leq 0.05$) with the ECEC of the soil in the 15 – 30 cm soil depth. These correlations supports previous research where it was found that ameliorating acidity and nutrient problems in the subsoil results in greater crop response (Farina *et al*., 2000). It is therefore crucial that the subsoil acidity does not remain unaddressed and therefore a one-off strategic tillage may incorporate liming material and result in uniformly distributed soil nutrients. A one-off strategic tillage has been found to have no severely detrimental effects on soil health and it could be argued that the advantages outweigh the detrimental effects (Azam and Gazey, 2020; Labuschagne *et al*., 2020). Subsoil acidity has been found to be widespread throughout the no-tillage production systems of the Western Cape, therefore subsoil acidity may potentially already be a limiting factor in these, or similar, production systems (Liebenberg *et al.*, 2020).

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### 4.5 Conclusions

The results from this trial do not support the in-row application of a small amount of micro-fine lime pellets as a viable option to ameliorate soil acidity in production systems with similar soil and climatic conditions. Opposed to a general recommendation in industry that a small amount of micro-fine lime can effectively alleviate soil acidity, no response was observed in this trial.

Results also show that the effectiveness of broadcasting micro-fine lime pellets is comparable to broadcasting Class A lime in these soil and climatic conditions. Therefore, it may not be recommended for producers in similar climatic conditions and production systems to apply the more expensive product of the two options, the micro-fine lime pellets, since this product did not sufficiently outperform the Class A lime in this production system and climate to warrant the higher cost of buying this product.

A one-off tillage action may be an effective strategy to create a more uniform distribution of chemical properties throughout the entire soil profile. All three tillage treatments (disc, rip and chisel ploughs) resulted in similar outcomes in these soil and climatic conditions. Similar outcomes were obtained both on soil properties and in the crop response of both canola and wheat. It is therefore not possible to recommend a specific tillage method in these conditions for these crops or for the soil properties.

Addressing soil $pH_{(KCl)}$ in the subsoil may result in a positive crop response, both in the growth of the crop and the quality of the grain yield at the end of the season. The application of liming material had an influence on both canola and wheat, although the overall yields were still comparable, differences in crop quality were observed between treatments. It is difficult to determine whether the lack of meaningful differences between multiple variables in the canola was due to the slow reaction of limestone or due to the resilience of the canola crop.

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# Chapter 5: Conclusion and Recommendations

## 5.1 Synopsis

No-tillage has been widely adopted in the annual crop production systems around the globe (Derpsch *et al.*, 2010). The Western Cape Province of South Africa is no exception, with approximately 80% of producers in this province having converted to no-tillage (Smith *et al.*, 2017). The producers in the southern Cape and Swartland regions of the Western Cape are responsible for > 50% of wheat (*Triticum aestivum*), >85% of barley (*Hordeum vulgare*) and 100% of South Africa's canola (*Brassica napus*) production (USDA, 2015; Mogala, 2017; De Kock, 2018).

The lack of physical incorporation of liming materials into no-tilled soils have led to the development of soil acidity stratification in the long term (Barth *et al.*, 2018). Stratification of soil acidity was found throughout the Western Cape Province, especially in the Swartland region (Liebenberg *et al.*, 2020). The development of stratification is to be expected, since the slow movement of lime in soils is well understood (Caires *et al.*, 2008; Ernani *et al.*, 2004).

Positive crop responses of barley, wheat and canola to the application of liming material have been reported, and where liming resulted in no crop response, the lack of response was ascribed to the liming material not neutralising soil acidity in the rooting zone of the crop (Scott et al., 2003; Caires et al., 2006; Godsey *et al*., 2007; Flower and Crabtree, 2011). The positive response of crops to the application of liming material, especially in the rooting zone, along with the widespread subsoil acidity found in annual crop production systems, emphasise the need for subsoil acidity to be addressed. A one-off strategic tillage has been found to have no severe detrimental effects on soil health and is an effective strategy to obtain a chemically uniform soil profile (Labuschagne et al., 2020; Azam and Gazey, 2020). Therefore, the use of a one-off tillage may have both the benefits of mixing liming material into the soil profile as well as obtaining a chemically uniform soil profile through the mixing of soil layers where stratification of soil acidity may already be present.

Aside from the physical incorporation of liming material into the soil profile, the choice of liming material to apply is also a difficult decision. There are various forms and chemical purities of liming material available on the market, yet there are some questions raised

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regarding the efficiency of the more expensive forms and higher chemical purities of liming materials. In addition to these different forms and chemical purities of liming materials, producers may further be confused by industry claims that the application of a small amount of micro-fine lime pellets will neutralise the same amount of soil acidity than the broadcast application of a typical amount of Class A calcitic lime.

The form, fineness, and placement of liming materials, along with the choice of whether to incorporate a one-off strategic tillage, and which implement to use, may all influence the result of the liming of soils. Therefore, this study had three objectives:

1) The first objective was to conduct a survey to determine the geographical spread and severity of pH stratification in long term no-tillage soils across the Western Cape.

2) The second objective was to determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on soil chemical attributes.

3) The third objective was to determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on the growth and development of canola and wheat.

### 5.1.1 Objective 1: To conduct a survey to determine the geographical spread and severity of pH stratification in long term no-tillage soils across the Western Cape Province

Acidity has been found in the soils of the Western Cape Province, with the Swartland region having more severe acidity problems than the southern Cape region. Of the fields sampled in the Swartland, 19.3% of soils had at least one depth increment where the soil $pH_{(KCl)}$ was ≤ 5.0. In addition to the abundance of soils with $pH_{(KCl)}$ ≤ 5.0, stratification of acidity and nutrients was found over increasing soil depth. The levels of acid saturation measured in the 5 – 15 cm depth increment in the Swartland was higher than the threshold given for the production of wheat.

### 5.1.2 Objective 2: To determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on soil chemical attributes

The broadcast application of limestone at the recommended rate, or at 19% lower than the recommended rate, neutralises topsoil acidity in a slightly acidic soil such as was found on this

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trial site, regardless of whether Class A calcitic lime or micro-fine lime pellets are applied. The duration of this trial was however too short for the applied liming materials to completely neutralise soil acidity, although some effect was observed, in the 5 – 15 cm depth layer. This study will, however, continue beyond the timeframe in which this MSc study was conducted.

Chemical purity, expressed as calcium carbonate equivalence (CCE), also did not yield substantial differences in soil properties or crop response. Therefore, it may not be economical in similar no-tillage production systems or climatic conditions to purchase a more expensive Class A calcitic lime, with a higher CCE, since the 95% CCE no-tillage treatment did not sufficiently outperform the 88% CCE no-tillage treatment. This is however highly dependant on location, as transport is a large fraction of the overall cost of liming materials in South Africa. A higher CCE product may also have economic advantages. Less product of a higher CCE material is required, which may translate to substantially lower transport costs, depending on the quantity required.

The type of soil disturbance (rip, chisel or disc ploughs) did not yield substantially differing results on soil properties or crop response. All three of the tillage treatments resulted in the most uniform soil profile in terms of soil chemical properties measured.

The in-row placement of micro-fine lime pellets at a rate of 40 kg $ha^{-1}$ is not sufficient to neutralise soil acidity in the area of placement, since the soil samples of the in-row application did not indicate the neutralisation of higher amounts of soil acidity than the samples taken between crop rows.

### 5.1.3 Objective 3: To determine, by means of a field trial, the effect of form, fineness, and placement of limestone, with and without soil disturbance, on the growth and development of canola and wheat

The crop response in the various variables measure to tillage treatments were all comparable between canola and wheat respectively. All the disturbance treatments resulted in high leaf area indices (LAI's) for canola and aboveground biomass yield similar to all other treatments. For wheat, rip plough disturbance resulted in the lowest plant population, however all other crop measurements, including grain yield and quality, were similar ($p$ > 0.05) to the other tillage- and the no tillage treatments. Of the wheat grain yields, the three highest yielding treatments were the treatments where soil was disturbed, although these treatments were

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similar ($p > 0.05$) to all other treatments. In terms of wheat quality, the disturbance treatments resulted in the highest, or similar to the highest, values for all the wheat quality variables measured.

For the no tillage treatments, there were few differences in the results of the variables measured for canola and wheat. Therefore, for these soil and climatic conditions under no-tillage management, there is no clear difference between the broadcast applications of Class A calcitic lime or micro-fine lime pellets. The higher cost of micro-fine lime pellets could potentially deter producers from purchasing this product, since these crop results do not indicate that micro-fine lime pellets sufficiently outperform the Class A calcitic lime.

**5.2 General conclusion**

Soil acidity is prevalent throughout the no-tillage production systems of the Western Cape. In addition to the geographical spread of soil acidity, stratification thereof is found over increasing soil depth. Thus, soil acidity should not only be addressed in the various regions where it is prevalent, but the method of addressing soil acidity is also important, since the stratification of acidity also needs to be addressed. A strategic one-off soil tillage, following a broadcast application of liming material, may be the most effective method to address soil acidity problems and obtain a soil profile that is more uniform in physical and chemical properties. Under these soil and climatic conditions, Class A calcitic lime and micro-fine lime pellets yielded similar response in soil properties and crop response. The in-row application of a small amount of micro-fine lime pellets did not ameliorate soil acidity beyond that of broadcast lime application. In-row application of micro-fine lime pellets resulted in a lower ($p \leq 0.05$) increase in Ca content of the soil than the broadcast lime applications. Soil properties and crop responses were positively influenced by tillage treatments, in most cases, and the tillage treatments also had the most uniform distribution of soil properties. Therefore, the aim of this study, which was to determine the most effective liming strategies for crop rotation systems in the Western Cape of South Africa, has been reached. The most effective liming strategy is broadcast application of Class A lime, following the physical incorporation of the liming material with either of the implements evaluated in this trial. Even though broadcast application of micro-fine lime pellets yielded similar results on soil properties and crop response, Class A calcitic lime is recommended due to the lower cost thereof.

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## 5.3 Limitations of research

The initial soil samples taken in the field to determine the lime requirement, were not representative of the trial site. This resulted in an overestimation of the actual lime requirement. Therefore, the results from this trial may have been different, had a different trial location, with more severe soil acidity problems, been selected.

The results from this trial may also have been different, had a crop other than canola been established in the same year as the application of the treatments. Crop response to liming of soils is dependent on the crop used, therefore a different crop to canola may have shown different responses in the various variables that were measured. Due to the resilience of the canola crop, some treatment differences may not have been observed in the year that limestone application was done.

Soil samples taken at the end of 2020, along with continuation of this trial in 2021, may potentially result in meaningful results for both the soil properties and crop response of a crop established on the same soil in 2021. The continuation of the trial in 2021 may therefore result in data that can substantiate or contradict the conclusions from this trial over the previous two years. Continuation of the trial over a longer period could potentially mitigate the climatic differences from year to year and may therefore contribute to determining which differences in variables are ascribed to treatment effects, crop differences or climatic factors.

## 5.4 Recommendations for future research

The financial implications that some of the treatments may have on producers, may undermine the viability of those treatments for commercial use. This is specifically applicable to the treatments where lime pellets were broadcasted, which may be uneconomical for producers. The results from this trial do not support the broadcasting of lime pellets over the use of Class A calcitic lime, since both forms of lime resulted in similar results. Therefore, it may be a better option for commercial applicability to combine an in-row application of lime pellets with a broadcast application of Class A calcitic lime. In future trials, combinations of in-row applications of micro-fine lime pellets and broadcast applications of Class A calcitic lime could be evaluated.

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### 5.5 References

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# Appendix A

**Appendix A.** The published version of the soil survey is available at the following reference:

Liebenberg, A., Van der Nest, J.R.R., Hardie, A.G., Labuschagne, J., Swanepoel, P.A. 2020. Extent of soil acidity in no-tillage systems in the Western Cape province of South Africa. *Land,* 9, p361.

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# Appendix B

**Appendix B.** Questionnaire that was given to each producer included in the soil survey (Chapter 3).

## SOIL ACIDITY SURVEY QUESTIONNAIRE

### INTRODUCTION

Adriaan Liebenberg and Ruan van der Nest are MSc students at Stellenbosch University who are doing a survey about soil acidity and liming methods on farms where conservation agriculture principles are being followed. The goal of the survey is to obtain a geographical image of the spread of subsoil acidity throughout the southern Cape and the Swartland areas. All information will remain anonymous.

### SECTION A: GENERAL MANAGEMENT ON FARM

1. How is the lime requirement for application determined, with soil sampling or a set amount as part of the system?

Soil sampling ☐
Set amount/ maintenance quantity ☐

1.1. If soil sampling is done:

To which depth? ________________________________

1.2. If set amount:

What rate of lime is routinely applied? ___________________________

2. Are Albrecht-principles being followed to determine lime requirement?

Yes ☐

No ☐

I am unfamiliar with the Albrecht-system ☐

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3. How long ago was lime applied? ____________________________

4. Which lime source is used?

Calcitic ☐

Dolomitic ☐

According to need ☐

5. Which form of lime is applied?

Class A (normal lime) ☐

Hydrated lime ☐

Granules ☐

Other: ___________________________

6. Please describe the implement that is used to apply lime:

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

________________________

7. When is liming done?

Post-harvest ☐ Before planting ☐ During planting ☐

8. Is liming done with precision farming (GPS guided in field)?

Yes ☐ No ☐

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9. Are calcium (Ca) fertilisers also applied?

Yes ☐

No ☐

According to need ☐

Calcium source if known: ______________________

**Take note: LAN is 3% Ca*

10. When is calcium fertiliser applied?

Post-harvest ☐ Before planting ☐ During planting ☐

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**SECTION B: CAMP SPECIFIC INFORMATION**

Please provide the following information for the four fields where soil samples will be taken:

| | | | | |
|---|---|---|---|---|
| Camp number | | | | |
| Crop rotation that is followed in this specific field | | | | |
| Which crop will be planted in the current season? | | | | |
| How much calcium fertiliser was applied in the last application? | | | | |
| Which source of calcium is applied? | | | | |
| Additional notes about the specific camp that may be worth mentioning | | | | |

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# Appendix C

**Appendix C.** Soil sample analyses for the trial site, prior to the start of the trial. CEC = cation exchange capacity; ECEC = effective cation exchange capacity.

| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol $kg^{-1}$) | Acid Saturation (%) | Ca (mg $kg^{-1}$) | Ca (%) | Mg (mg $kg^{-1}$) | Mg (%) | CEC (cmol $kg^{-1}$) | ECEC (cmol $kg^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0-5 | 5.4 | 0.48 | 4.80 | 1234.00 | 64.95 | 181.20 | 15.89 | 9.50 | 9.98 | 95.19 |
| 1 | 2 | 1 | 0-5 | 6.0 | 0.00 | 0.00 | 1600.00 | 70.18 | 198.00 | 14.47 | 11.40 | 11.40 | 100.00 |
| 1 | 3 | 1 | 0-5 | 5.9 | 0.00 | 0.00 | 1498.00 | 72.02 | 177.60 | 14.23 | 10.40 | 10.40 | 100.00 |
| 1 | 4 | 1 | 0-5 | 5.9 | 0.00 | 0.00 | 1106.00 | 65.83 | 165.60 | 16.43 | 8.40 | 8.40 | 100.00 |
| 1 | 5 | 1 | 0-5 | 6.2 | 0.00 | 0.00 | 1770.00 | 74.37 | 187.20 | 13.11 | 11.90 | 11.90 | 100.00 |
| 1 | 6 | 1 | 0-5 | 5.8 | 0.00 | 0.00 | 1518.00 | 72.29 | 176.40 | 14.00 | 10.50 | 10.50 | 100.00 |
| 1 | 7 | 1 | 0-5 | 5.5 | 0.52 | 5.36 | 1346.00 | 73.15 | 165.60 | 15.00 | 9.20 | 9.72 | 94.65 |
| 1 | 8 | 1 | 0-5 | 6.3 | 0.00 | 0.00 | 1700.00 | 78.70 | 160.80 | 12.41 | 10.80 | 10.80 | 100.00 |
| 1 | 9 | 1 | 0-5 | 5.6 | 0.00 | 0.00 | 1196.00 | 73.83 | 147.60 | 15.19 | 8.10 | 8.10 | 100.00 |
| 1 | 10 | 1 | 0-5 | 5.6 | 0.00 | 0.00 | 1288.00 | 70.77 | 168.00 | 15.38 | 9.10 | 9.10 | 100.00 |
| 1 | 11 | 2 | 0-5 | 5.6 | 0.00 | 0.00 | 1200.00 | 73.17 | 126.00 | 12.80 | 8.20 | 8.20 | 100.00 |
| 1 | 12 | 2 | 0-5 | 5.9 | 0.00 | 0.00 | 1398.00 | 74.36 | 142.80 | 12.66 | 9.40 | 9.40 | 100.00 |
| 1 | 13 | 2 | 0-5 | 6.0 | 0.00 | 0.00 | 1524.00 | 79.38 | 129.60 | 11.25 | 9.60 | 9.60 | 100.00 |
| 1 | 14 | 2 | 0-5 | 5.5 | 0.41 | 4.46 | 1342.00 | 76.25 | 142.80 | 13.52 | 8.80 | 9.21 | 95.55 |
| 1 | 15 | 2 | 0-5 | 5.9 | 0.00 | 0.00 | 1478.00 | 73.90 | 152.40 | 12.70 | 10.00 | 10.00 | 100.00 |
| 1 | 16 | 2 | 0-5 | 5.7 | 0.00 | 0.00 | 1398.00 | 69.21 | 141.60 | 11.68 | 10.10 | 10.10 | 100.00 |
| 1 | 17 | 2 | 0-5 | 5.6 | 0.00 | 0.00 | 1270.00 | 64.14 | 159.60 | 13.43 | 9.90 | 9.90 | 100.00 |
| 1 | 18 | 2 | 0-5 | 5.8 | 0.00 | 0.00 | 1502.00 | 70.85 | 160.80 | 12.64 | 10.60 | 10.60 | 100.00 |
| 1 | 19 | 2 | 0-5 | 6.0 | 0.00 | 0.00 | 1654.00 | 73.84 | 183.60 | 13.66 | 11.20 | 11.20 | 100.00 |
| 1 | 20 | 2 | 0-5 | 5.5 | 0.52 | 4.86 | 1468.00 | 71.96 | 186.00 | 15.20 | 10.20 | 10.72 | 95.15 |

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| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol kg$^{-1}$) | Acid Saturation (%) | Ca (mg kg$^{-1}$) | Ca (%) | Mg (mg kg$^{-1}$) | Mg (%) | CEC (cmol kg$^{-1}$) | ECEC (cmol kg$^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 21 | 3 | 0-5 | 6.0 | 0.00 | 0.00 | 1664.00 | 69.33 | 241.20 | 16.75 | 12.00 | 12.00 | 100.00 |
| 1 | 22 | 3 | 0-5 | 5.9 | 0.00 | 0.00 | 1660.00 | 69.75 | 242.40 | 16.97 | 11.90 | 11.90 | 100.00 |
| 1 | 23 | 3 | 0-5 | 6.0 | 0.00 | 0.00 | 1684.00 | 73.22 | 182.40 | 13.22 | 11.50 | 11.50 | 100.00 |
| 1 | 24 | 3 | 0-5 | 5.7 | 0.00 | 0.00 | 1330.00 | 67.86 | 153.60 | 13.06 | 9.80 | 9.80 | 100.00 |
| 1 | 25 | 3 | 0-5 | 4.9 | 0.73 | 8.80 | 1094.00 | 71.97 | 130.80 | 14.34 | 7.60 | 8.33 | 91.24 |
| 1 | 26 | 3 | 0-5 | 5.9 | 0.00 | 0.00 | 1692.00 | 75.54 | 165.60 | 12.32 | 11.20 | 11.20 | 100.00 |
| 1 | 27 | 3 | 0-5 | 5.8 | 0.00 | 0.00 | 1312.00 | 72.09 | 153.60 | 14.07 | 9.10 | 9.10 | 100.00 |
| 1 | 28 | 3 | 0-5 | 5.0 | 0.78 | 11.30 | 900.00 | 73.77 | 106.80 | 14.59 | 6.10 | 6.88 | 88.66 |
| 1 | 29 | 3 | 0-5 | 5.2 | 0.56 | 7.27 | 1030.00 | 72.54 | 123.60 | 14.51 | 7.10 | 7.66 | 92.69 |
| 1 | 30 | 3 | 0-5 | 5.6 | 0.00 | 0.00 | 1288.00 | 74.02 | 132.00 | 12.64 | 8.70 | 8.70 | 100.00 |
| 1 | 31 | 4 | 0-5 | 6.1 | 0.00 | 0.00 | 1544.00 | 76.44 | 171.60 | 14.16 | 10.10 | 10.10 | 100.00 |
| 1 | 32 | 4 | 0-5 | 6.0 | 0.00 | 0.00 | 1426.00 | 72.76 | 164.40 | 13.98 | 9.80 | 9.80 | 100.00 |
| 1 | 33 | 4 | 0-5 | 5.6 | 0.00 | 0.00 | 1292.00 | 74.25 | 145.20 | 13.91 | 8.70 | 8.70 | 100.00 |
| 1 | 34 | 4 | 0-5 | 5.2 | 0.59 | 7.28 | 1094.00 | 72.93 | 126.00 | 14.00 | 7.50 | 8.09 | 92.71 |
| 1 | 35 | 4 | 0-5 | 6.1 | 0.00 | 0.00 | 1464.00 | 77.87 | 140.40 | 12.45 | 9.40 | 9.40 | 100.00 |
| 1 | 36 | 4 | 0-5 | 5.8 | 0.00 | 0.00 | 1486.00 | 70.76 | 192.00 | 15.24 | 10.50 | 10.50 | 100.00 |
| 1 | 37 | 4 | 0-5 | 5.8 | 0.00 | 0.00 | 1308.00 | 72.67 | 150.00 | 13.89 | 9.00 | 9.00 | 100.00 |
| 1 | 38 | 4 | 0-5 | 6.4 | 0.00 | 0.00 | 2182.00 | 74.22 | 212.40 | 12.04 | 14.70 | 14.70 | 100.00 |
| 1 | 39 | 4 | 0-5 | 6.3 | 0.00 | 0.00 | 1936.00 | 74.46 | 214.80 | 13.77 | 13.00 | 13.00 | 100.00 |
| 1 | 40 | 4 | 0-5 | 5.9 | 0.00 | 0.00 | 1362.00 | 68.79 | 177.60 | 14.95 | 9.90 | 9.90 | 100.00 |

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| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol kg$^{-1}$) | Acid Saturation (%) | Ca (mg kg$^{-1}$) | Ca (%) | Mg (mg kg$^{-1}$) | Mg (%) | CEC (cmol kg$^{-1}$) | ECEC (cmol kg$^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 5-15 | 5.5 | 0.49 | 5.83 | 1150.00 | 72.78 | 146.40 | 3.92 | 7.9 | 8.39 | 94.16 |
| 1 | 2 | 1 | 5-15 | 5.8 | 0.00 | 0.00 | 1208.00 | 71.90 | 153.60 | 3.33 | 8.4 | 8.40 | 100.00 |
| 1 | 3 | 1 | 5-15 | 5.8 | 0.00 | 0.00 | 1248.00 | 73.41 | 163.20 | 3.53 | 8.5 | 8.50 | 100.00 |
| 1 | 4 | 1 | 5-15 | 5.7 | 0.00 | 0.00 | 1236.00 | 72.71 | 174.00 | 3.53 | 8.5 | 8.50 | 100.00 |
| 1 | 5 | 1 | 5-15 | 5.8 | 0.00 | 0.00 | 1194.00 | 73.70 | 153.60 | 3.83 | 8.1 | 8.10 | 100.00 |
| 1 | 6 | 1 | 5-15 | 5.5 | 0.47 | 5.28 | 1262.00 | 75.12 | 157.20 | 5.36 | 8.4 | 8.87 | 94.70 |
| 1 | 7 | 1 | 5-15 | 5.0 | 0.74 | 9.49 | 1038.00 | 74.14 | 134.40 | 4.43 | 7.0 | 7.74 | 90.44 |
| 1 | 8 | 1 | 5-15 | 5.5 | 0.45 | 5.36 | 1208.00 | 76.46 | 145.20 | 4.56 | 7.9 | 8.35 | 94.61 |
| 1 | 9 | 1 | 5-15 | 5.3 | 0.59 | 7.38 | 1118.00 | 75.54 | 142.80 | 4.86 | 7.4 | 7.99 | 92.62 |
| 1 | 10 | 1 | 5-15 | 5.2 | 0.61 | 7.63 | 1058.00 | 71.49 | 153.60 | 7.16 | 7.4 | 8.01 | 92.38 |
| 1 | 11 | 2 | 5-15 | 4.9 | 0.77 | 11.00 | 928.00 | 74.84 | 118.80 | 4.84 | 6.2 | 6.97 | 88.95 |
| 1 | 12 | 2 | 5-15 | 5.3 | 0.52 | 7.88 | 898.00 | 73.61 | 109.20 | 5.08 | 6.1 | 6.62 | 92.15 |
| 1 | 13 | 2 | 5-15 | 4.9 | 0.72 | 10.14 | 976.00 | 76.25 | 112.80 | 5.00 | 6.4 | 7.12 | 89.89 |
| 1 | 14 | 2 | 5-15 | 5.4 | 0.54 | 7.20 | 1070.00 | 76.43 | 117.60 | 4.29 | 7.0 | 7.54 | 92.84 |
| 1 | 15 | 2 | 5-15 | 5.4 | 0.51 | 6.46 | 1156.00 | 79.18 | 106.80 | 3.29 | 7.3 | 7.81 | 93.47 |
| 1 | 16 | 2 | 5-15 | 5.2 | 0.69 | 8.02 | 1180.00 | 74.68 | 132.00 | 3.80 | 7.9 | 8.59 | 91.97 |
| 1 | 17 | 2 | 5-15 | 5.3 | 0.54 | 6.67 | 1058.00 | 70.53 | 122.40 | 2.93 | 7.5 | 8.04 | 93.28 |
| 1 | 18 | 2 | 5-15 | 5.6 | 0.00 | 0.00 | 1224.00 | 72.00 | 147.60 | 2.24 | 8.5 | 8.50 | 100.00 |
| 1 | 19 | 2 | 5-15 | 5.9 | 0.00 | 0.00 | 1574.00 | 74.95 | 180.00 | 2.00 | 10.5 | 10.50 | 100.00 |
| 1 | 20 | 2 | 5-15 | 5.2 | 0.72 | 8.00 | 1160.00 | 70.73 | 170.40 | 3.41 | 8.2 | 8.92 | 91.93 |

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| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol kg$^{-1}$) | Acid Saturation (%) | Ca (mg kg$^{-1}$) | Ca (%) | Mg (mg kg$^{-1}$) | Mg (%) | CEC (cmol kg$^{-1}$) | ECEC (cmol kg$^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 21 | 3 | 5-15 | 5.0 | 0.83 | 8.56 | 1204.00 | 68.41 | 225.60 | 4.66 | 8.8 | 9.63 | 91.38 |
| 1 | 22 | 3 | 5-15 | 5.4 | 0.63 | 7.08 | 1108.00 | 67.56 | 206.40 | 3.29 | 8.2 | 8.83 | 92.87 |
| 1 | 23 | 3 | 5-15 | 5.4 | 0.60 | 6.00 | 1320.00 | 70.21 | 182.40 | 2.45 | 9.4 | 10.00 | 94.00 |
| 1 | 24 | 3 | 5-15 | 5.5 | 0.51 | 5.67 | 1200.00 | 70.59 | 136.80 | 2.12 | 8.5 | 9.01 | 94.34 |
| 1 | 25 | 3 | 5-15 | 5.0 | 0.78 | 9.07 | 1138.00 | 72.03 | 145.20 | 5.57 | 7.9 | 8.68 | 91.01 |
| 1 | 26 | 3 | 5-15 | 5.6 | 0.00 | 0.00 | 1230.00 | 75.93 | 135.60 | 5.31 | 8.1 | 8.10 | 100.00 |
| 1 | 27 | 3 | 5-15 | 5.2 | 0.59 | 8.19 | 972.00 | 72.54 | 127.20 | 4.78 | 6.7 | 7.29 | 91.91 |
| 1 | 28 | 3 | 5-15 | 5.0 | 0.65 | 9.85 | 876.00 | 74.24 | 112.80 | 4.92 | 5.9 | 6.55 | 90.08 |
| 1 | 29 | 3 | 5-15 | 5.1 | 0.64 | 9.01 | 982.00 | 75.54 | 109.20 | 4.31 | 6.5 | 7.14 | 91.04 |
| 1 | 30 | 3 | 5-15 | 5.3 | 0.50 | 7.35 | 904.00 | 71.75 | 121.20 | 5.87 | 6.3 | 6.80 | 92.65 |
| 1 | 31 | 4 | 5-15 | 5.6 | 0.00 | 0.00 | 1022.00 | 71.97 | 148.80 | 5.63 | 7.1 | 7.10 | 100.00 |
| 1 | 32 | 4 | 5-15 | 5.4 | 0.48 | 5.65 | 1172.00 | 73.25 | 146.40 | 3.75 | 8.0 | 8.48 | 94.34 |
| 1 | 33 | 4 | 5-15 | 5.3 | 0.54 | 7.40 | 1014.00 | 75.67 | 115.20 | 4.18 | 6.7 | 7.24 | 92.54 |
| 1 | 34 | 4 | 5-15 | 5.1 | 0.57 | 6.95 | 1132.00 | 74.47 | 130.80 | 5.92 | 7.6 | 8.17 | 93.02 |
| 1 | 35 | 4 | 5-15 | 5.4 | 0.46 | 6.13 | 1050.00 | 75.00 | 130.80 | 5.29 | 7.0 | 7.46 | 93.83 |
| 1 | 36 | 4 | 5-15 | 5.5 | 0.47 | 4.85 | 1378.00 | 74.89 | 158.40 | 4.57 | 9.2 | 9.67 | 95.14 |
| 1 | 37 | 4 | 5-15 | 5.6 | 0.00 | 0.00 | 1268.00 | 71.24 | 170.40 | 5.28 | 8.9 | 8.90 | 100.00 |
| 1 | 38 | 4 | 5-15 | 5.5 | 0.51 | 4.40 | 1608.00 | 72.43 | 205.20 | 4.95 | 11.1 | 11.61 | 95.61 |
| 1 | 39 | 4 | 5-15 | 6.0 | 0.00 | 0.00 | 1772.00 | 73.83 | 230.40 | 2.75 | 12.0 | 12.00 | 100.00 |
| 1 | 40 | 4 | 5-15 | 5.8 | 0.00 | 0.00 | 1526.00 | 70.65 | 207.60 | 3.24 | 10.8 | 10.80 | 100.00 |

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| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol kg$^{-1}$) | Acid Saturation (%) | Ca (mg kg$^{-1}$) | Ca (%) | Mg (mg kg$^{-1}$) | Mg (%) | CEC (cmol kg$^{-1}$) | ECEC (cmol kg$^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 15-30 | 5.6 | 0.00 | 0.00 | 964.00 | 69.86 | 160.80 | 19.42 | 6.9 | 6.90 | 100.00 |
| 1 | 2 | 1 | 15-30 | 5.7 | 0.00 | 0.00 | 972.00 | 66.58 | 177.60 | 20.27 | 7.3 | 7.30 | 100.00 |
| 1 | 3 | 1 | 15-30 | 5.8 | 0.00 | 0.00 | 766.00 | 61.77 | 174.00 | 23.39 | 6.2 | 6.20 | 100.00 |
| 1 | 4 | 1 | 15-30 | 5.7 | 0.00 | 0.00 | 842.00 | 61.01 | 187.20 | 22.61 | 6.9 | 6.90 | 100.00 |
| 1 | 5 | 1 | 15-30 | 5.7 | 0.00 | 0.00 | 992.00 | 67.95 | 171.60 | 19.59 | 7.3 | 7.30 | 100.00 |
| 1 | 6 | 1 | 15-30 | 5.3 | 0.46 | 6.22 | 966.00 | 69.00 | 169.20 | 20.14 | 7.0 | 7.46 | 93.83 |
| 1 | 7 | 1 | 15-30 | 5.1 | 0.53 | 7.91 | 908.00 | 73.23 | 128.40 | 17.26 | 6.2 | 6.73 | 92.12 |
| 1 | 8 | 1 | 15-30 | 5.3 | 0.54 | 8.44 | 800.00 | 67.80 | 145.20 | 20.51 | 5.9 | 6.44 | 91.61 |
| 1 | 9 | 1 | 15-30 | 5.2 | 0.45 | 6.62 | 850.00 | 67.46 | 160.80 | 21.27 | 6.3 | 6.75 | 93.33 |
| 1 | 10 | 1 | 15-30 | 5.3 | 0.55 | 7.75 | 824.00 | 62.42 | 171.60 | 21.67 | 6.6 | 7.15 | 92.31 |
| 1 | 11 | 2 | 15-30 | 4.9 | 0.57 | 8.38 | 892.00 | 70.79 | 142.80 | 18.89 | 6.3 | 6.87 | 91.70 |
| 1 | 12 | 2 | 15-30 | 5.1 | 0.55 | 8.09 | 878.00 | 69.68 | 139.20 | 18.41 | 6.3 | 6.85 | 91.97 |
| 1 | 13 | 2 | 15-30 | 5.1 | 0.54 | 8.44 | 822.00 | 69.66 | 136.80 | 19.32 | 5.9 | 6.44 | 91.61 |
| 1 | 14 | 2 | 15-30 | 5.2 | 0.50 | 7.14 | 942.00 | 72.46 | 134.40 | 17.23 | 6.5 | 7.00 | 92.86 |
| 1 | 15 | 2 | 15-30 | 5.3 | 0.45 | 6.62 | 974.00 | 77.30 | 114.00 | 15.08 | 6.3 | 6.75 | 93.33 |
| 1 | 16 | 2 | 15-30 | 5.3 | 0.43 | 5.44 | 1102.00 | 73.47 | 146.40 | 16.27 | 7.5 | 7.93 | 94.58 |
| 1 | 17 | 2 | 15-30 | 5.5 | 0.39 | 5.57 | 900.00 | 68.18 | 142.80 | 18.03 | 6.6 | 6.99 | 94.42 |
| 1 | 18 | 2 | 15-30 | 5.6 | 0.00 | 0.00 | 866.00 | 65.61 | 164.40 | 20.76 | 6.6 | 6.60 | 100.00 |
| 1 | 19 | 2 | 15-30 | 5.5 | 0.45 | 5.29 | 1034.00 | 64.63 | 220.80 | 23.00 | 8.0 | 8.45 | 94.67 |
| 1 | 20 | 2 | 15-30 | 5.4 | 0.55 | 6.71 | 1052.00 | 69.21 | 176.40 | 19.34 | 7.6 | 8.15 | 93.25 |

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| Date number | Plot no. | Block | Depth (cm) | pH (KCl) | Exchangeable Acidity (cmol kg$^{-1}$) | Acid Saturation (%) | Ca (mg kg$^{-1}$) | Ca (%) | Mg (mg kg$^{-1}$) | Mg (%) | CEC (cmol kg$^{-1}$) | ECEC (cmol kg$^{-1}$) | Base Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 21 | 3 | 15-30 | 5.2 | 0.54 | 6.43 | 992.00 | 62.78 | 250.80 | 26.46 | 7.9 | 8.44 | 93.60 |
| 1 | 22 | 3 | 15-30 | 5.3 | 0.46 | 6.22 | 844.00 | 60.29 | 241.20 | 28.71 | 7.0 | 7.46 | 93.83 |
| 1 | 23 | 3 | 15-30 | 5.5 | 0.45 | 4.55 | 1350.00 | 71.05 | 207.60 | 18.21 | 9.5 | 9.95 | 95.48 |
| 1 | 24 | 3 | 15-30 | 5.4 | 0.51 | 6.00 | 1128.00 | 70.50 | 163.20 | 17.00 | 8.0 | 8.51 | 94.01 |
| 1 | 25 | 3 | 15-30 | 5.2 | 0.52 | 6.93 | 1032.00 | 73.71 | 142.80 | 17.00 | 7.0 | 7.52 | 93.09 |
| 1 | 26 | 3 | 15-30 | 5.2 | 0.53 | 7.16 | 1008.00 | 73.04 | 139.20 | 16.81 | 6.9 | 7.43 | 92.87 |
| 1 | 27 | 3 | 15-30 | 5.2 | 0.45 | 6.72 | 852.00 | 67.62 | 156.00 | 20.63 | 6.3 | 6.75 | 93.33 |
| 1 | 28 | 3 | 15-30 | 5.0 | 0.62 | 10.51 | 762.00 | 71.89 | 120.00 | 18.87 | 5.3 | 5.92 | 89.53 |
| 1 | 29 | 3 | 15-30 | 5.2 | 0.60 | 10.00 | 782.00 | 72.41 | 112.80 | 17.41 | 5.4 | 6.00 | 90.00 |
| 1 | 30 | 3 | 15-30 | 5.3 | 0.46 | 6.87 | 898.00 | 71.27 | 128.40 | 16.98 | 6.3 | 6.76 | 93.20 |
| 1 | 31 | 4 | 15-30 | 5.3 | 0.39 | 5.91 | 846.00 | 67.14 | 154.80 | 20.48 | 6.3 | 6.69 | 94.17 |
| 1 | 32 | 4 | 15-30 | 5.2 | 0.46 | 7.19 | 836.00 | 70.85 | 132.00 | 18.64 | 5.9 | 6.36 | 92.77 |
| 1 | 33 | 4 | 15-30 | 5.2 | 0.49 | 7.90 | 840.00 | 73.68 | 117.60 | 17.19 | 5.7 | 6.19 | 92.08 |
| 1 | 34 | 4 | 15-30 | 5.3 | 0.41 | 6.31 | 878.00 | 71.97 | 123.60 | 16.89 | 6.1 | 6.51 | 93.70 |
| 1 | 35 | 4 | 15-30 | 5.4 | 0.49 | 7.21 | 914.00 | 72.54 | 135.60 | 17.94 | 6.3 | 6.79 | 92.78 |
| 1 | 36 | 4 | 15-30 | 5.2 | 0.40 | 5.97 | 928.00 | 73.65 | 132.00 | 17.46 | 6.3 | 6.70 | 94.03 |
| 1 | 37 | 4 | 15-30 | 5.5 | 0.40 | 5.41 | 962.00 | 68.71 | 164.40 | 19.57 | 7.0 | 7.40 | 94.59 |
| 1 | 38 | 4 | 15-30 | 5.6 | 0.00 | 0.00 | 1150.00 | 69.28 | 186.00 | 18.67 | 8.3 | 8.30 | 100.00 |
| 1 | 39 | 4 | 15-30 | 6.1 | 0.00 | 0.00 | 1282.00 | 62.84 | 303.60 | 24.80 | 10.2 | 10.20 | 100.00 |
| 1 | 40 | 4 | 15-30 | 5.7 | 0.00 | 0.00 | 1184.00 | 69.65 | 177.60 | 17.41 | 8.5 | 8.50 | 100.00 |